3 ARCHIPELAGIC COMPARISONS

In this chapter, integrated ecosystem observations collected during Mariana Archipelago Reef Assessment and Monitoring Program (MARAMP) cruises in 2003, 2005, and 2007 are compared between islands across the Mariana Archipelago. These discussions address the following topics: geopolitical context, benthic habitat mapping and characterization, oceanography and water quality, corals and coral disease, algae and algal disease, benthic macroinvertebrates, reef fishes, species of concern, marine debris, and ecosystem-wide integration. The spatial patterns and variability of observations of coral reef ecosystems around individual islands and banks are examined on a regional scale. This broad-scale examination provides information relevant to ecosystem-based management and conservation of the coral reefs around these islands and banks at local, regional, national, and international levels. Note that many of the tables and figures in this chapter show islands from north to south and use 3-letter codes for island names; island codes are provided in the List of Abbreviations in this report.

Other chapters of this report present—on an individual island or bank basis—comprehensive and detailed spatial and temporal descriptions of the integrated coral reef ecosystem observations recorded during MARAMP 2003, 2005, and 2007. MARAMP surveys were conducted around the island of Guam and 3 adjacent offshore banks (11-mile Reef, Santa Rosa Reef, and Galvez Bank) in the territory of Guam and around 13 islands (Rota, Aguijan, Tinian, Saipan, Anatahan, Sarigan, Guguan, Alamagan, Pagan, Agrihan, Asuncion, Maug, and Farallon de Pajaros), 5 offshore banks (Tatsumi Reef, Esmeralda Bank, Marpi Bank, Zealandia Bank, and Supply Reef) in the Commonwealth of the Northern Mariana Islands (CNMI), and 3 remote reefs (Pathfinder Reef, Arakane Reef, and Stingray Shoal) on the West Mariana Ridge.

3.1   Geopolitical Context

This section summarizes some of the available socioeconomic and geopolitical data about Guam and the CNMI to aid analyses of coral reef ecosystems in the context of human activities that may be influencing them. Many of the anthropo-

T able 3.1a. Summary of island parameters across the Mariana Archipelago: land area, proportion of archipelagic population, population density, maximum elevation, native vegetation, vegetation cover, and animal threats (U.S. Bureau of the Census 2011a, 2011b; Siebert and Simkin 2002– ; Encyclopaedia Britannica Online; Cruz et al. 2000a, 2000b, 2000c, 2000d, 2000e; Cruz et al. 2003; Esselstyn et al. 2003; Liu and Fischer 2006a, 2006b; Mueller-Dombois and Fosberg 1998; Pacific Protected Areas Database; Martin et al. 2008; Minton 2005; National Park Service 2001, 2005; Stafford et al. 2005; Atkinson and Atkinson 2000; Burdick et al. 2008; Fritts and Leasman-Tanner 2001; Fritts and Rodda 1998; Marianas Avifauna Conservation Working Group 2008; Rodda and Savidge 2007; M Onni, CNMI Division of Fish and Wildlife, pers. comm.). Land areas were calculated using Geographic Information System (GIS) techniques.

Island	Land Area (km^2)	Share of Arch. Population (% in 2000)	Population Density (persons/km^2)	Maximum Elevation (m)	Year of Last Eruption	Native Vegetation	Vegetation Cover (%)	Animal Threats
FDP	2.25	0	0	360	1967	L	L	None
MAU	2.14	0	0	227	–	M	M	goat, rat
ASC	7.86	0	0	857	1906	H	M	rat
AGR	44.05	0	0	965	1917	M	H	goat, pig, rat
PAG	47.75	0	0	570	2010	L	M	cattle, goat, pig, rat
ALA	12.96	0	0	744	870	L	M	goat, cat, pig, rat
GUG	4.24	0	0	287	1883	H	M	rat
SAR	4.47	0	0	538	–	M	M	rat, eradicated: goat, cat, pig
ANA	33.91	0	0	788	2008	M?	L	goat, pig, rat
SAI	118.98	22.6	405.3	474	–	VL	M	cattle, goat, brown tree snake, cat, pig, rat
TIN	101.22	1.5	31.0	187	–	VL	H	cattle, goat, brown tree snake, cat, pig, rat
AGU	7.01	0	0	57	–	M	H	goat, rat
ROT	85.13	1.2	29.7	496	–	M	H	cattle, goat, brown tree snake, cat, pig, rat
GUA	544.34	74.7	292.8	406	–	VL	M	cattle, goat, brown tree snake, cat, pig, rat

VL: very low, L: low, M: medium, H: high, VH: very high   🐂 cattle, 🐐 goat, 🐍, * 🐍 brown tree snake, 🐈 cat, 🐖 pig, 🐀 rat

* Indicates brown tree snake sighted but not established

genic activities and effects on the coral reef ecosystems in this region are concentrated around the 4 populated, southern islands. Although a few anthropogenic issues, such as feral animals, introduced species, and fishing, affect the ecosystems of the uninhabited or sporadically populated northern islands, natural events, including storms and volcanic eruptions, presumably generate most ecological disturbances in the northern islands. Table 3.1a presents a summary of selected physical, social, and environmental attributes that have been identified in the island chapters of this report as potential sources of effects on coral reef ecosystems. Additional information regarding history and demographics, geographic and geologic settings, land use, economy, and environmental issues is discussed for each island and bank in their respective chapters and on a regional basis in Chapter 1: "Introduction."

3.1.1   History and Demographics

A native Chamorro population was established in the Mariana Archipelago as early as 3500 years ago (Rogers 1995) and declined significantly during the period of control by Spain. Estimates of the Chamorro population prior to the arrival of the first Spanish missionaries in the late 17th century range from 24,000 to 100,000, significantly higher than the 3539 Chamorro recorded in the first Spanish census in 1710 (Rogers 1995; Underwood 1973). The total human population in the Mariana Archipelago surged during and after World War II (WWII) to more than 65,000 by 1950 and has increased to more than 200,000 in recent years, although the population in the CNMI declined between the 2 most recent U.S. Decennial Cenuses (Fig. 3.1.1a; U.S. Bureau of the Census 1982, 1983, 2002, 2003, 2011a, 2011b; Office of the High Commissioner 1959). Guam and Saipan are the most densely populated islands (Table 3.1a) with 74.7% and 22.6% of the archipelagic population in 2010 and population densities of 292.8 and 405.3 persons km^{-2}, respectively (U.S. Bureau of the Census 2011a, 2011b). The 4 populated, southern islands of Guam, Rota, Tinian, and Saipan supported the entire population of the Mariana Archipelago in 2010, according to the U.S. Census 2010, although the previous U.S. Census in 2000 had an official count of 6 persons for the northern islands and sporadic, small populations of < 300 persons combined have been recorded on the northern islands of Agrihan, Pagan, Alamagan, and Anatahan since WWII (U.S. Bureau of the Census 2003, 2011a, 2011b; Cruz et al. 2000a; Siebert and Simkin 2002–; University of Hawaii 2009; Trefalt 2003).

Guam accounted for three-fourths of the estimated 2010 population for the Mariana Archipelago with 159,358 persons (U.S. Bureau of the Census 2011a, 2011b). Guam's population is expected to grow by an estimated 24,713 as the U.S. military relocates between 4700 and 8000 Marines, as well as other personnel and dependents, to the island within the next decade (U.S. Department of the Navy 2010; Parrish 2012; Hart 2012). Civilian population is also expected to increase to provide construction and other services for the military buildup (Laney 2008). Some military-related population growth is expected in the CNMI, but that increase could be offset by population declines related to other sectors of the economy. In

Figure 3.1.1a. Population growth (U.S. Bureau of the Census 1982, 1983, 1992, 2002, 2003, 2011a, 2011b; CNMI Department of Commerce 2002a; Secretariat of the Pacific Community 2011) and visitor count (Bank of Hawaii 1995; Lucas 1990; U.S. Department of the Interior 1996; CNMI Department of Commerce 2002b; Marianas Visitors Authority; A Cid, Guam Visitors Bureau, pers. comm.) trends on Guam and the CNMI during the period of 1965 to 2015.
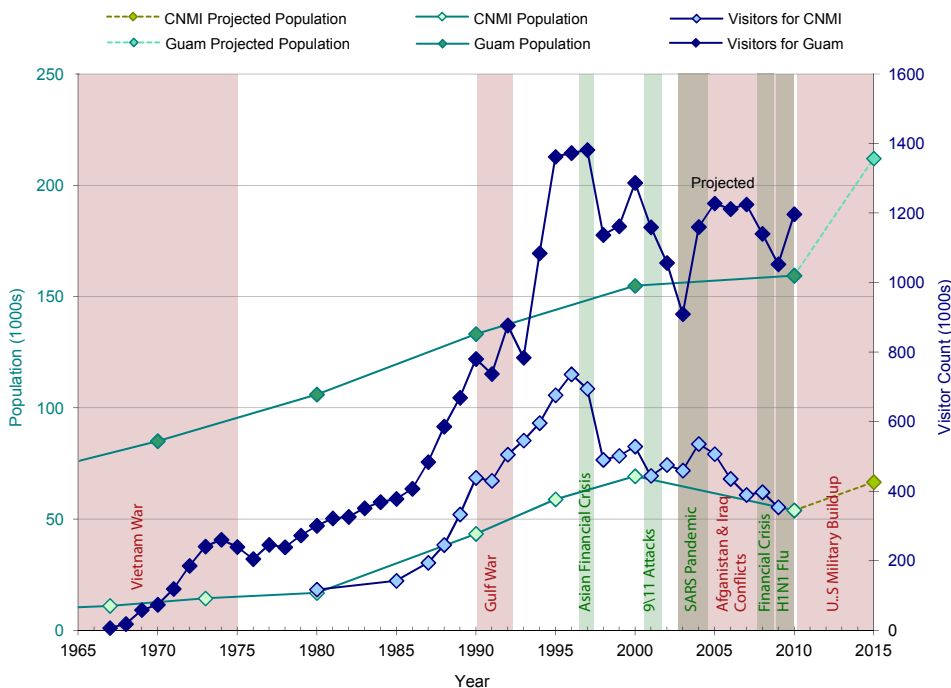
the CNMI, the estimated population dropped more than 22% from 69,221 in 2000 to 53,883 in 2010 (U.S. Bureau of the Census 2003, 2011a). Legislation signed into law in 2010 may lead to the repopulation of some of the northern islands, including Sarigan, Alamagan, Pagan, and Agrihan.

3.1.2   Land Cover and Use

The major differences in land use between the southern and northern islands are primarily related to human population. In terms of land cover, WWII events in the southern islands played a significant role in determining the amount of native vegetation that remained. In recent decades, the southern islands have seen growth in military development and tourism, exacerbating land-use pressures associated with population growth and infrastructure support. In contrast, the sparsely populated, northern islands are largely removed from these development issues.

During WWII, U.S. troops captured Guam, Tinian, and Saipan from Japanese forces after fierce fighting in the summer of 1944. During and after these battles, large portions of the native limestone forests and ground cover on these 3 islands were completely destroyed. Subsequent recolonization of terrestrial flora often involved replacement with non-native plant species (Pacific Worlds & Associates 2003). Because no prolonged battles were fought on Rota or Aguijan, which Japan surrendered at the end of WWII, much more native limestone forest remains on these two islands than on Guam, Saipan, and Tinian. Estimates suggest that Rota still has land cover of more than 50% native limestone forest (Liu and Fischer 2006a).

On Saipan and Guam, 25%–50% of the land use has been classified as urban (Liu and Fischer 2006a, 2006b; see Fig. 4.1.2a in Chapter 4: "Guam and Adjacent Reefs and Banks," Section 4.1.2: "Land Use" and Fig. 8.1.3a in Chapter 8: "Saipan," Section 8.1.3: "Geography"). The land area of Saipan is only 22% of the land area of Guam, and Saipan's population density is 1.8 times greater than Guam's population density (U.S. Bureau of the Census 2002, 2003, 2008). Geographically, the human population on Guam is largely centered in the northern part of that island, while population is more evenly spread across the island of Saipan. The population density and urbanization of these 2 most heavily populated islands are also significant factors in the land cover and other environmental issues that can affect coral reefs (e.g., pollution, arson of hillside vegetation, construction, erosion, recreational overuse, excessive fishing). On Tinian and Rota, population centers are much smaller, with less associated urban development.

Beyond population density, major potential determinants in land cover include volcanic activity and the presence of feral animals introduced by previous and current human inhabitants. On the northern islands, land cover is influenced by the steepness of the stratovolcanoes and the amount, frequency, and duration of volcanic eruptions, which cause deposits of ash or lava, mass wasting, or erosion. On almost all islands of the Mariana Archipelago, introduced feral animals, including goats, pigs, deer, and cows, destroy or alter native understory vegetation—destruction that can increase erosion and runoff and can, therefore, have significant indirect effects on coral reef ecosystems. Currently, only Farallon de Pajaros is thought to have no introduced feral animals, although Guguan and Asuncion have only rats (Atkinson and Atkinson 2000; Burdick et al. 2008; Cruz et al. 2000a, 2000b, 2000c, 2000d, 2000e; Cruz et al. 2003; Esselstyn et al. 2003; Fritts and Leasman-Tanner 2001; Fritts and Rodda 1998; Martin et al. 2008; Marianas Avifauna Conservation Working Group 2008; National Park Service 2005; Pacific Protected Areas Database; Rodda and Savidge 2007).

3.1.3   Geology and Geomorphology

The differences in the geologic histories of the islands of the Mariana Archipelago have been identified together as a major factor that shapes the coral reef ecosystems surrounding these islands (Burdick et al. 2008; Houk and Van Woesik 2010; Riegl et al. 2008). The 6 southernmost islands of Guam, Rota, Aguijan, Tinian, Saipan, and Farallon de Medinilla and their adjacent banks are part of the Mariana frontal arc, consist of extinct volcanic edifices that were formed in the late Eocene to early Miocene epochs (15–20 million years ago), and are largely covered by layered, uplifted carbonate surfaces (see Figs. 1.1.2a and 1.1.2b in Chapter 1: "Introduction," Section 1.1: "Geologic and Geographic Setting"). These carbonate surfaces are flat-lying and have low slopes except between layers. Some limestone areas exhibit karst topographies, which are formed by dissolution of carbonate rocks and characterized by sinkholes, caves, and subterranean passages. Because of high limestone porosity on these southern islands, there is little surface-water retention or runoff. On these 6 islands, the underlying volcanic rocks are exposed in only a few places, except on Guam, where most of the southern half of this island consists of exposed Eocene volcanic rocks and laterite soils, which are highly susceptible to erosion, especially on the steep southwestern coast (see Fig. 4.1.2a in Chapter 4: "Guam and Adjacent Reefs and Banks," Section 4.1.2: "Land Use").

The 9 northern islands of the Mariana Archipelago are all part of the active Mariana Arc created by the subduction of the Pacific Plate under the Philippine Plate. Seven of these islands—Anatahan, Guguan, Alamagan, Pagan, Agrihan, Asuncion, and Farallon de Pajaros—are either currently active or have been active within recorded history (Fig. 3.1.3a and Table 3.1a). Most recently, the latest recorded eruption occurred in 2010 at Pagan, which experienced a major eruption in 1981. The last recorded eruption at Anatahan ended in 2008, and this island experienced major eruptions in 2003 and 2005. Although Farallon de Pajaros has not been active since 1967, this northernmost island was known in previous centuries as the "Lighthouse of the Pacific" because of frequent eruptions. The first known eruption of a volcano in the Mariana Archipelago, based on radiocarbon dating, was of Alamagan in AD 540 (Siebert and Simkin 2002–).

Figure 3.1.3a. Island age, primary geology, and eruptive volcanic activity in the Mariana Archipelago. Eruption information is based on historic records and radiocarbon dating back to AD 540 (Siebert and Simkin 2002–).
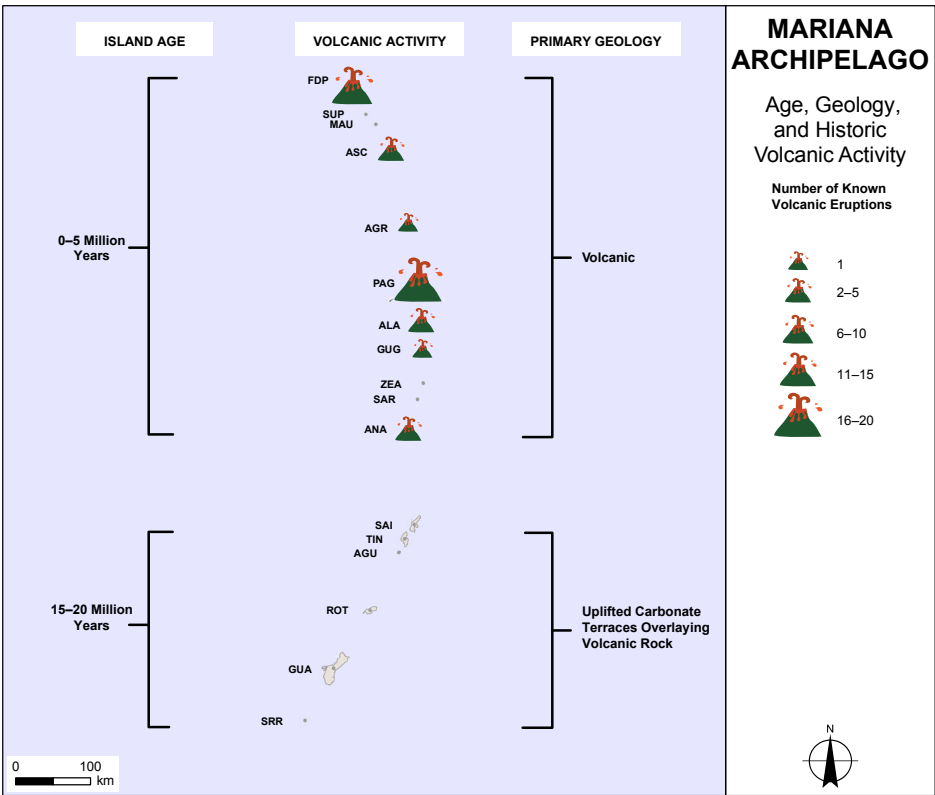
Two geomorphologic features potentially are important factors when considering the composition and condition of the coral reef ecosystems that surround the islands of the Mariana Archipelago: island land area and slope, both above and below the surface of the ocean. Slope is closely related to the geology and elevation of each island. The northern islands, characterized by steep profiles and periodic, explosive eruptions, are all stratovolcanoes (i.e., tall, conical volcanoes with many layers or strata of hardened lava, cinder, or volcanic ash; Fig. 3.1.3b). These volcanoes originate from the seafloor at depths of ≥ 2000 m and rise to maximum elevations ranging from 227 m (Maug) to 965 m (Agrihan) above sea level. Among the southern islands, the highest point is on the Sabana Plateau on Rota at 496 m; this high point is very near the south shore, and the steep slope in that area is subject to erosion.

The northern volcanic islands, as a group, are much steeper than the southern carbonate islands. Rota, Tinian, and Aguijan are primarily flat, step-like carbonate plateaus with steep slopes only between the different limestone layers. Southern Guam and northern Saipan have steeper slopes and more complex topography where volcanic rocks are exposed. On the northern islands, north Farallon de Pajaros, Maug, east Asuncion, north Agrihan, east Alamagan, south Sarigan, and north Anatahan have slopes in excess of 30°, and evidence of frequent landslides has been noted during biennial MARAMP surveys around these islands, especially on Farallon de Pajaros and Asuncion.

Islands range in size from a mere 2 km^2 for Maug and Farallon de Pajaros to 544 km^2 for Guam, and the total area for all 9 of the northern islands from Anatahan north to Farallon de Pajaros is only 160 km^2 (Table 3.1a).

Figure 3.1.3b. Farallon de Pajaros, a steep-sided stratovolcano with little vegetation, has had at least 15 eruptions since the first known one for this island was recorded in 1864. *NOAA photo*

3.1.4   Economy

The primary drivers of Guam's economy are tourism and the large, growing presence of the U.S. military and government. The economy of the CNMI is based primarily on tourism (Laney 2008), having lost the once-booming garment industry in Saipan. For both the CNMI and Guam, significant economic effects have resulted from fluctuations in visitor arrivals from Asia associated with global economic, political, and environmental changes, including regional recessions, the terrorist attacks on September 11, 2001, and concerns over severe acute respiratory syndrome and bird flu. The economic forecast for Guam is relatively strong because of increasing military investment and recent improvement in the tourism industry. In contrast, economic drivers in the CNMI generally are weak because visitor arrivals have decreased dramatically from their peak in 1996 and garment industry revenues essentially have disappeared.

Tourism, particularly from Asian markets, has been a major component of the economies of both the CNMI and Guam since the 1980s. Tourism suffered during the weakness of Asian economies in the 1990s. Since 2005, the decline in Japanese visitors and the related cuts in the number of direct flights from Asia to Guam or Saipan have further hurt these markets. The number of visitors arriving in the CNMI fell to 353,956 in 2009, a 52% drop from 736,117 in 1996 (CNMI Department of Commerce 2002b; Marianas Visitors Authority), while Guam's visitor arrivals decreased only slightly from a high of 1,381,513 in 1997 to 1,196,523 in 2010 (A Cid, Guam Visitors Bureau, pers. comm.). Guam in recent years has experienced increased tourism from Russia and China, both key markets for future growth (Guam Visitors Bureau). The CNMI has seen a rise in visitors from Russia but a decline in combined arrivals from China and Hong Kong each year beginning in 2007, although combined arrivals from China and Hong Kong are up dramatically from counts in 2002 (Marianas Visitors Authority). Ongoing discussions about immigration laws and their effect on tourism center on visitor eligibility for Chinese and Russian travelers under the Guam-CNMI Visa Waiver Program.

Guam has been a strategic U.S. military post in the Pacific for much of the past century. With the withdrawal of troops from the Philippines in the 1980s and the planned move of ~ 25,000 military personnel and family members, including at least 4700 Marines from Japan, to Guam in the next decade (U.S. Department of the Navy 2010; Parrish 2012; Hart 2012), Guam has become an even more important location for U.S. military operations in the western Pacific. This projected population increase and associated spending for construction, harbor, and housing projects over the next decade will be a major factor in Guam's future, economically and environmentally. In the CNMI, the U.S. Department of Defense leases 60% of Tinian for training, conducts live-fire exercises on Farallon de Medinilla, and pays for anchoring strategic "pre-positioned" ships in the Garapan Anchorage on the west side of Saipan. Use of Pagan and other northern islands for military training has been proposed. Still, the level of military spending in the CNMI is relatively low when compared to the projected $15 billion to be spent in Guam over a decade (Laney 2008).

The garment industry was a key driver of the economy on Saipan, beginning in the 1980s and peaking in 1998. As world trade opened and minimum wage requirements rose, however, Saipan's garment industry became much less competitive, and the last garment factory on Saipan closed in February 2009. In 2008, the U.S. Congress passed legislation to federalize immigration to the CNMI, which not only may have affected what remained of the garment industry but also could have considerable effect on tourism and foreign investment (U.S. Government Accountability Office [GAO] 2008).

Other sectors of the economies of Guam and the CNMI, such as fishing and agriculture, are relatively minor in their economic impacts but are culturally important. Most fishing is conducted from shore or on small vessels, primarily around the populated islands, although some vessels do fish near the northern islands. Documented local fishing issues in Guam and Saipan are discussed in the individual chapters. Agriculture is a small source of income (CNMI Department of Commerce 2008; Guam Department of Labor 2008; National Park Service 2005).

3.1.5   Environmental Issues

Many of the environmental concerns in Guam are associated with increasing population, tourism, and development. Construction of facilities for ~ 25,000 incoming military personnel and dependents is a major concern for some residents of Guam. Although the human population and tourism in the CNMI has declined in recent years, pressures from human activities still affect the coral reef ecosystems around the populated, southern islands. Military construction of piers and training facilities and ranges could potentially affect ecosystems on and around Tinian, Saipan, Pagan, and other islands in the CNMI. Tourism and associated facility construction and tourist activities, such as diving and other water sports, that can affect coral reefs are vital issues in both Guam and the CNMI, since their economies depend on tourism (Burdick et al. 2008). Fishing pressure is another concern around the southern islands of the Mariana Archipelago; fishing efforts have been stable or increased and fish catch rates have declined over the past 20 years in Guam (Burdick et al. 2008).

Coastal pollution associated with sewage outfalls, sedimentation, and runoff is a concern in most populated areas. The majority of freshwater resources on Guam and the southern, populated islands of the CNMI come from underground lenses that rest on top of saltwater lenses at or near sea level. Elevation of sea level caused by global warming possibly could affect the level of available freshwater resources (Titus 1990). In 2008, both landfills and wastewater systems on Guam were reported to be at capacity (GAO 2009). An average of 700 wildfires per year from 1979 to 2006 have been set on Guam intentionally by poachers and hunters, resulting in deforestation, land erosion, and increased sedimentation, which is one of the most significant threats to the reefs around Guam (Burdick et al. 2008).

To date, widespread mass coral bleaching and widespread coral disease have not been observed around Guam or the CNMI, although restricted outbreaks have been detected at Guam and Saipan (Burdick et al., 2008; Starmer et al. 2008). Climate change potentially could increase the frequency and severity of typhoons in one of the most active regions for tropical storms in the world; an average of 3 typhoons per year have passed within 540 km of the southern islands of the Mariana Archipelago since 1970 (Landers 2004). In addition to climate change, another factor that potentially can impact coral reef health is periodic outbreaks of crown-of-thorns seastars (COTS) that have been observed around several islands during MARAMP surveys.

In the northern, largely uninhabited islands of the CNMI, the frequency, duration, and magnitude of active volcanism can severely affect coral reef ecosystems. At Anatahan during MARAMP 2003, for example, many coral heads were observed to be covered by ashfalls. Steep slopes or absence of land cover can cause active mass wasting, landslides into the ocean, or erosion. Feral animals and a potential increase in fishing are also concerns for these northern islands.

The CNMI and Guam, as well as the federal government, have set aside a number of marine protected areas (MPAs) in recent years:

- Guam designated 5 marine preserves in 1997 with a total area of 36 km^2. Protection of these areas has been documented to improve fish stocks within these limited-take and no-take reserves (Burdick et al. 2008). Two ecological preserves were designated in 1984 with a total area of 1.68 km^2; however, legislation (Guam Public Law 29-127) that may once again open these reserves to fishing by indigenous peoples was passed in 2008.
- Sasanhaya Fish Reserve on Rota was established in 1994 and encompasses an area of 0.8 km^2. Although it is a no-take reserve, enforcement never has been implemented fully in this MPA (Starmer et al. 2008).
- Around Saipan, 3 no-take MPAs with a total area of 12.1 km^2 were designated in 2000 and 2001: Managaha Marine Conservation Area, Bird Island Marine Sanctuary, and Forbidden Island Marine Sanctuary.

- In 2008, the CNMI designated a new marine reserve for Tinian, but the exact boundaries and, thus, the total size of this MPA are yet to be defined.
- The islands of Guguan, Asuncion, Maug, and Farallon de Pajaros, with a total land area of 16.5 km², were set aside as protected areas in 1985 by an amendment to Article XIV of the CNMI Constitution.
- The waters and submerged lands surrounding Asuncion, Maug, and Farallon de Pajaros to a seaward boundary of 50 nmi together form the Islands Unit of the Marianas Trench Marine National Monument, which was established by presidential proclamation in 2009 and encompasses 246,608 km² in the Mariana Archipelago.

3.2   Benthic Habitat Mapping and Characterization

The nearshore waters of the Mariana Archipelago were surveyed by the Coral Reef Ecosystem Division (CRED) and several other NOAA and academic groups. A synthesis of the collected multibeam bathymetric data is presented in Figure 3.2a. These data were used to estimate the size and structure of potential benthic habitats available for colonization of coral reef communities around each island or bank. The high-resolution bathymetric data from all multibeam and lidar surveys, when combined with less accurate estimated depths from satellite sources (e.g., multispectral imagery and satellite altimetry from gravity readings) and the 100-fm (~ 200 m) chart boundary, allow for calculation of approximate areas of seafloor in the following depth ranges: 0–30 m (where shallow, diver surveys were conducted), 30–100 m, and 100–200 m. Figures 3.2b and c and Table 3.2a provide an overview of the absolute and relative areas of seafloor within these depth boundaries throughout the Mariana Archipelago.
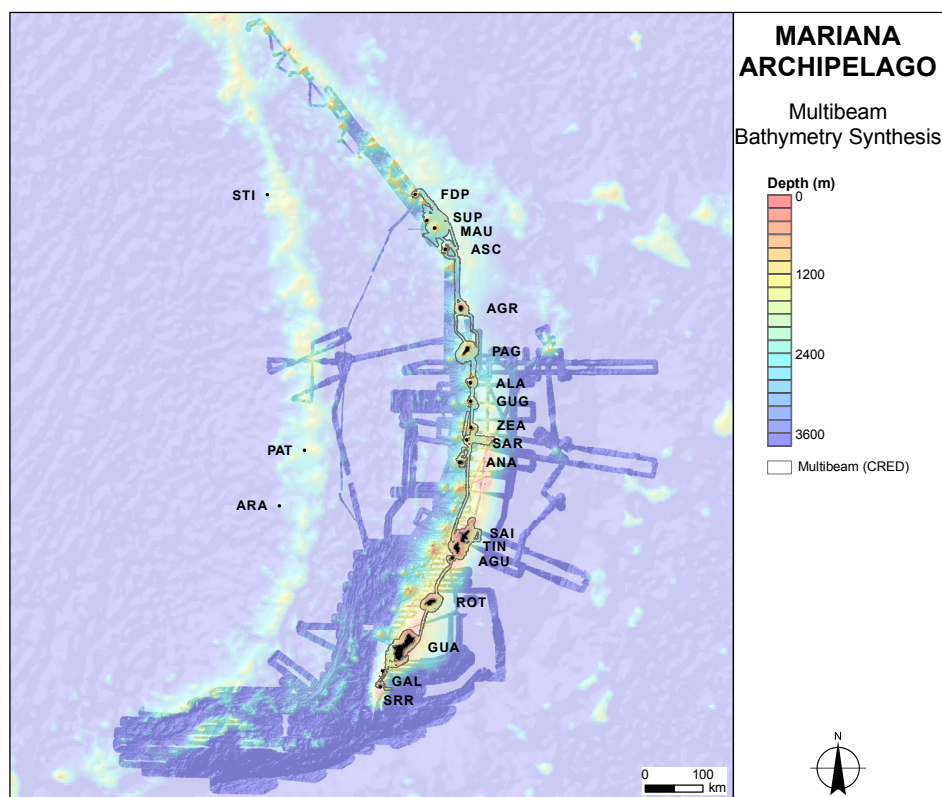
Figure 3.2a. Composite bathymetry based on various data sets available as of September 2007 for the Mariana Archipelago. The grey outline shows data collected during CRED surveys.

Figure 3.2b. Composition (%) of seafloor area at 3 depth ranges (0–30, 30–100, and 100–200 m) surrounding the islands and banks of the Mariana Archipelago. For seafloor areas (km²) at these depth ranges by island and bank, see Table 3.2a.
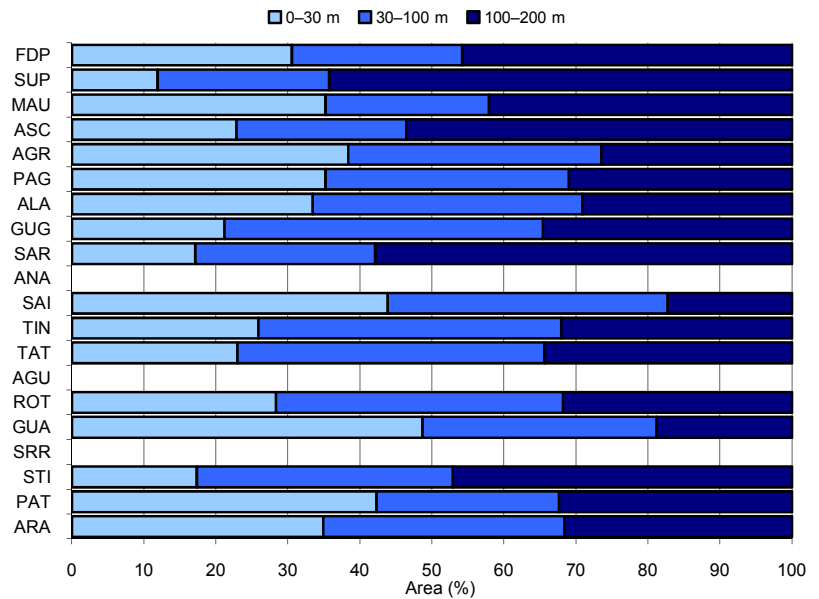
Figure 3.2c. Comparison of the land areas (km²) of the islands and banks of the Mariana Archipelago and the areas of seafloor (km²) at depths of 0–200 m surrounding these islands and banks.
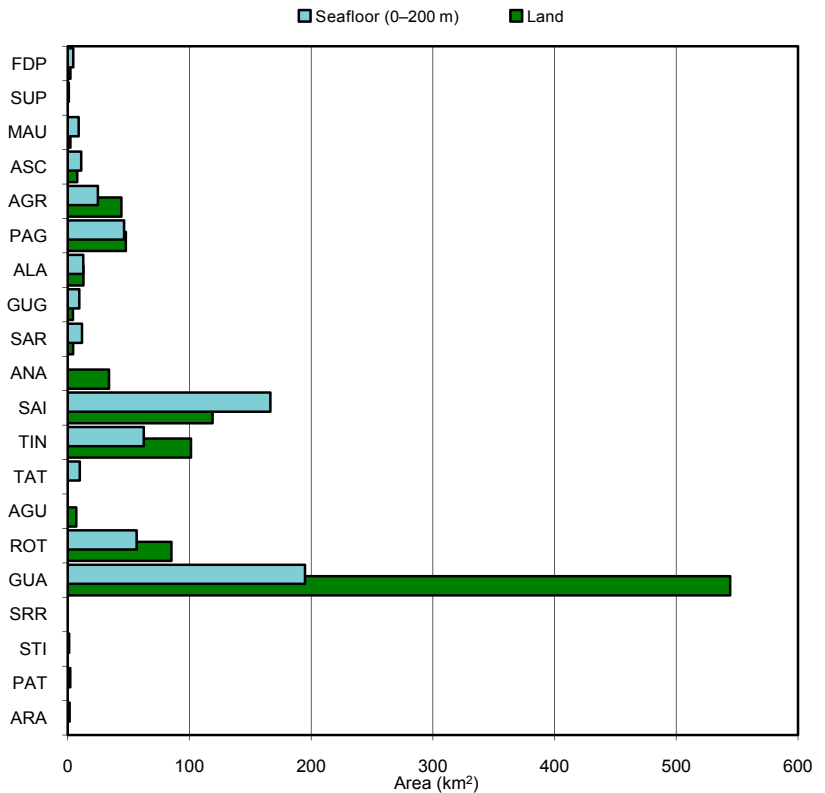
The land areas of the islands in the Mariana Archipelago range from 2.14 to 544.34 km². The seafloor areas surrounding these islands at the depth range of 0–30 m vary between 1.38 and 94.85 km², and, at the depth range of 0–200 m, they vary between 4.52 and 194.99 km² (Table 3.2b). Around the northern islands, the areas of seafloor at depths of 0–100 m, or the areas of potential benthic habitat, ranged only from 2.45 to 31.93 km², reflecting the steep topography around the northern stratovolcanoes. The areas for potential benthic habitat are larger around the southern islands, particularly around Saipan, than around the northern islands. A unique and sizeable feature, Saipan's Garapan Anchorage, largely accounts for the similarity in size of the potential habitat (137.25 and 158.32 km² at depths of 0–100 m) between Saipan and Guam, which has a land area more than 4 times as large as the land area of Saipan (Table 3.2c). In general, around most other islands in the Mariana Archipelago, the seafloor area in the depth range of 0–30 m is similar to the seafloor area in the depth range of 30–100 m.

Island	Land Area (km²)	Seafloor Area at Depths of 0–30 m (km²)	Seafloor Area at Depths of 30–100 m (km²)	Seafloor Area at Depths pf 100–200 m (km²)	Seafloor Area at Depths of 0–200 m (km²)	Combined Land and Seafloor (0-200 m) Area (km²)
FDP	2.25	1.38	1.07	2.07	4.52	6.77
SUP	–	0.10	0.20	0.54	0.84	0.84
MAU	2.14	3.17	2.04	3.79	9.00	11.14
ASC	7.86	2.54	2.62	5.96	11.12	18.98
AGR	44.05	9.50	8.70	6.56	24.76	68.81
PAG	47.75	16.29	15.64	14.34	46.27	94.02
ALA	12.96	4.28	4.79	3.73	12.80	25.76
GUG	4.24	2.00	4.18	3.27	9.45	13.69
SAR	4.47	2.00	2.92	6.76	11.68	16.15
ANA	33.91	–	–	–	–	33.91
SAI	118.98	73.04	64.63	28.82	166.49	285.47
TIN	101.22	16.20	26.31	20.04	62.55	163.77
TAT	–	2.26	4.20	3.39	9.85	9.85
AGU	7.01	–	–	–	–	7.01
ROT	85.13	16.03	22.54	18.00	56.57	141.70
GUA	544.34	94.85	63.47	36.67	194.99	739.33
SRR	–	–	–	–	–	–
STI	–	0.21	0.43	0.57	1.21	1.21
PAT	–	0.85	0.51	0.65	2.01	2.01
ARA	–	0.53	0.51	0.48	1.52	1.52

Table 3.2a. Land area per island or bank and seafloor areas categorized in depth ranges around each island and bank in the Mariana Archipelago. The "Combined Area (km²)" column provides the total of the land area plus the seafloor area at depths of 0–200 m for each island and bank.

Detailed multibeam bathymetry and backscatter products are discussed in the individual island chapters of this report. These results are presented in conjunction with analyses of video from towed optical assessment device (TOAD) surveys and observations from towed-diver surveys to improve understanding of benthic habitats around each island.

Archipelagic comparison of mean slope shows differences in both the land and underwater topographies of many of the islands in this region. Striking differences in slope can be noted between the northern islands, with seafloor slopes of 19°–25°, and the southern islands, with seafloor slopes of 10°–12° (Fig. 3.2d), and between the carbonate and volcanic geology of north and south Guam. Slope, volcanic eruption, and earthquake activity are all factors that influence mass wasting and landslides around each island. These factors along with the more general, worldwide influences of sea-level change, glaciation and deglaciation, and vertical island movement (e.g., sinking and rising) form a complex relationship that determines the growth or destruction of coral reefs through time (Webster et al. 2009, Clague et al. 2002).
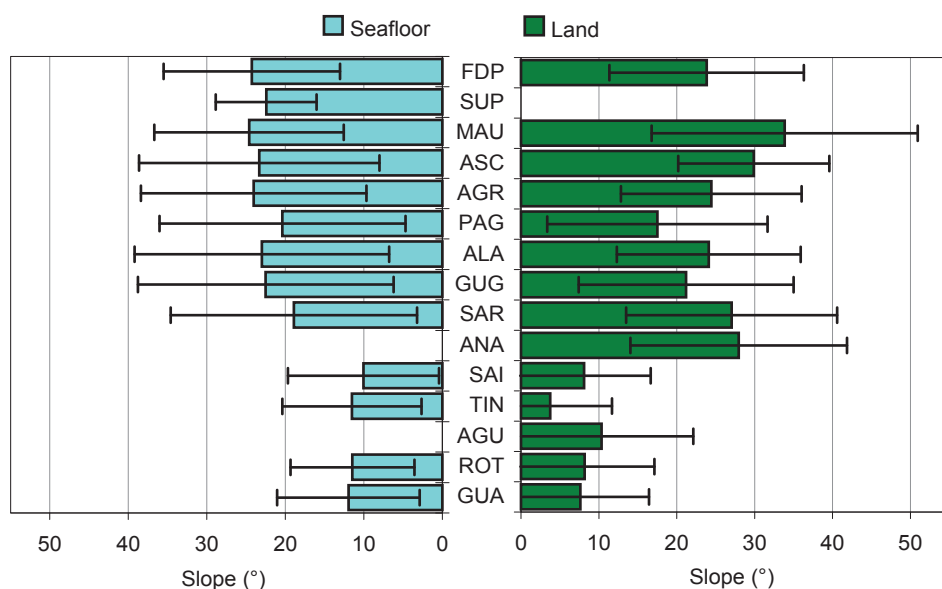
Figure 3.2d. Mean slope (*left*) of reefs around individual islands and Supply Reef in the Mariana Archipelago based on multibeam data collected at depths of ~ 1–2810 m during MARAMP 2003 and 2007 and (*right*) on land based on digital elevation models. Error bars indicate standard error (± 1 SE) of the mean.

Pooled benthic observations from towed-diver surveys conducted during MARAMP 2003, 2005, and 2007 suggest a general decrease in the islandwide means for sand cover progressing from the northern islands to the more populated, southern islands of the Mariana Archipelago (Figs. 3.2e and f).

Active volcanism in the northern part of the Mariana Archipelago likely plays an additional, key role in basaltic sand formation. At Anatahan, for example, the highest level of sand cover for an island in the Mariana Archipelago was recorded with an overall mean of 50% in 2003 (Fig. 3.2 f). Although high values of sand cover were recorded in raw data from towed-diver surveys conducted at Anatahan in 2003, the level of sand cover may likely have been overestimated because of ashfalls from a volcanic eruption that occurred earlier that year (see Chapter 9: "Anatahan," Sections 9.1 and 9.3: "Introduction" and "Benthic Habitat Mapping and Characterization;" for information about substrate categories used during towed-diver surveys, see Chapter 2: "Methods and Operational Background," Section 2.4.4: "Benthic Habitat Complexity and Substrates"). Anatahan, located between Sarigan and Saipan, was surveyed only in 2003.

Figure 3.2e. Cover (%) observations for corals, macroalgae, crustose coralline red algae, turf algae, sand, and the category "Other Anthozoans" from REA benthic surveys conducted using the line-point-intercept method on forereef habitats in the Mariana Archipelago during MARAMP 2007.

Figure 3.2f. Observations of sand cover (%) from towed-diver benthic surveys of forereef habitats conducted in the Mariana Archipelago during MARAMP 2003, 2005, and 2007. Error bars indicate standard error (± 1 SE) of the mean.

Benthic observations, pooled from towed-diver surveys conducted during the 3 MARAMP survey periods, also suggest that overall habitat complexity is higher around the 9 northern islands than around the 5 surveyed southern islands (Fig. 3.2g). The ge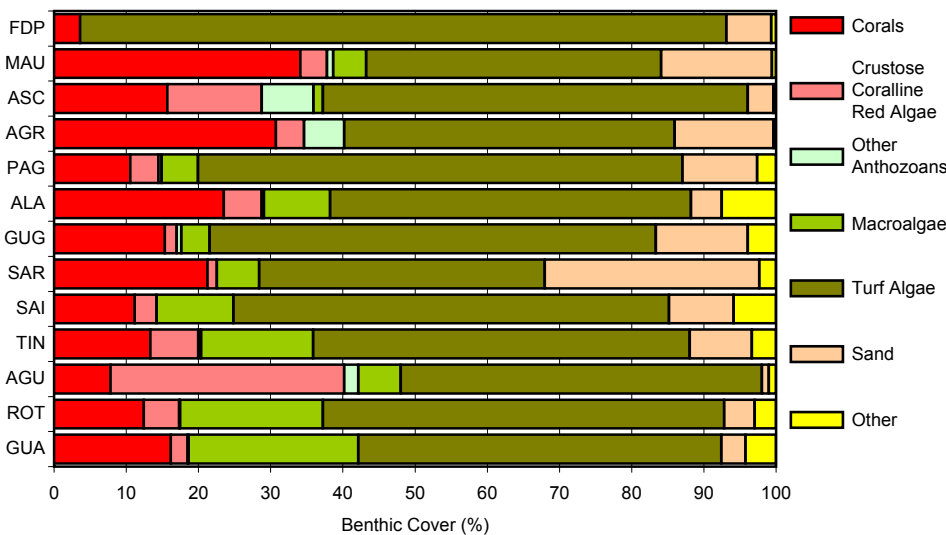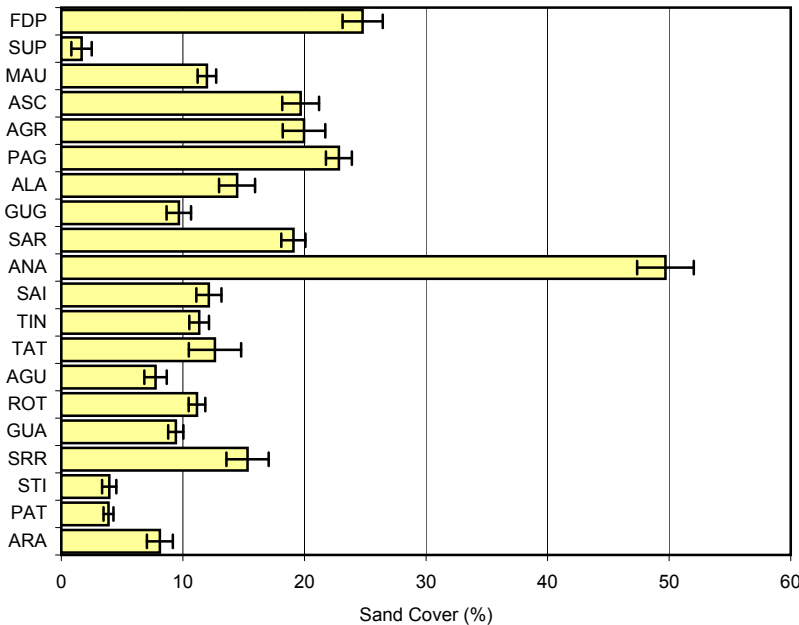ological differences between the northern and southern islands likely contribute to this habitat complexity pattern. The habitat types most consistently recorded at the northern islands during towed-diver surveys were rock boulders, interspersed with continuous reef and pavement. In contrast, reefs surrounding the southern islands were noted for habitats of pavement, continuous reef, and spur and groove. These observations largely match many of the elements in the satellite-derived, hierarchical classification scheme completed by the NOAA National Centers for Coastal Ocean Science (NCCOS) for shallow-water benthic habitats of the CNMI (NCCOS 2005). NCCOS identified dominant rock and boulder habitats around the northern islands of the Mariana Archipelago and classified habitats in the southern islands as pavement, aggregate reef, and spur-and-groove formation. Analysis focused on areas where overlap occurred between the NCCOS benthic classifications and towed-diver-survey tracks.
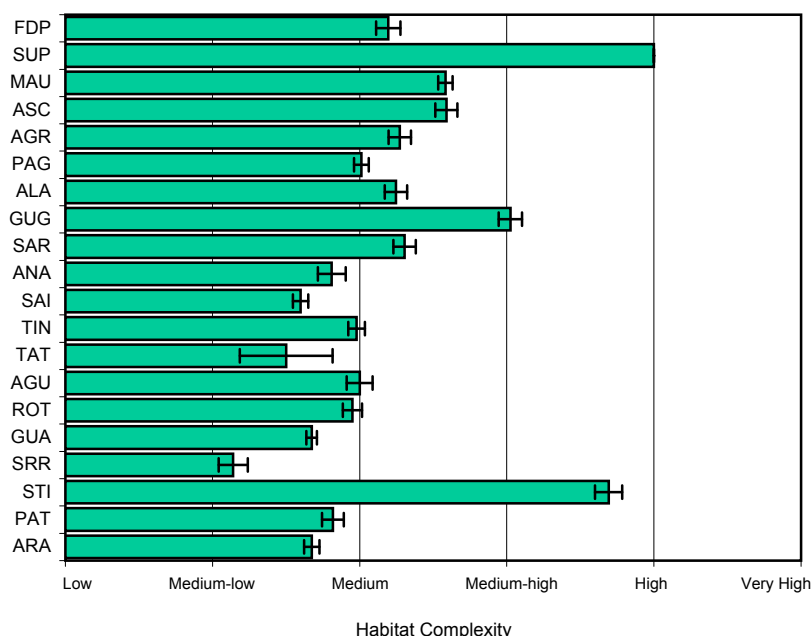
Figure 3.2g. Overall habitat complexity from towed-diver benthic surveys of forereef habitats conducted in the Mariana Archipelago during MARAMP 2003, 2005, and 2007. Habitat complexity is a relative measure from low to very high (see Chapter 2: "Methods and Operational Background," Section 2.4.4: "Benthic Habitat Complexity and Substrates"). Error bars indicate standard error (± 1 SE) of the mean.

3.3   Oceanography and Water Quality

The marine environment of the Mariana Archipelago is highly variable. Seasonal changes combined with the north–south orientation of this archipelago result in latitudinal gradients in oceanographic and meteorological conditions. This section presents remotely sensed, modeled, and in situ observations in a variety of formats (e.g., maps, time series, and climatologies) and describes long-term climatological averages of pertinent environmental, oceanographic, and meteorological parameters for each season, as well as the seasonal-to-interannual variability of these parameters. Satellite remotely sensed data and numerical modeling products provide important time series and climatological information. In situ data provide nearshore, subsurface information (e.g., nutrient concentrations) that is unattainable from satellites or that fluctuates on scales (spatial and temporal) too small for satellite instruments to measure. Throughout this section, 3 geographic designations are used for convenience to represent groups of islands: the "northernmost islands" encompass Farallon de Pajaros, Maug, and Asuncion, the "central islands" include Agrihan, Pagan, Alamagan, Guguan, Sarigan, and Anatahan, and the "southern islands" encompass Saipan, Tinian, Aguijan, Rota, and Guam.

3.3.1   Seasonal Climatologies

Satellite remote-sensing observations and modeled wave data were used to calculate long-term seasonal climatologies to describe the variability in forcing and latitudinal gradient of key environmental parameters, including wind, surface currents, sea-surface temperature (SST), chlorophyll-*a* (Chl-*a*) concentration, and ocean waves (see Chapter 2: "Methods and Operational Background," Section 2.3.7: "Satellite Remote Sensing and Ocean Modeling"). Climatologies for the region 12°–22° N and 140°–150° E are presented for each season: winter (January–March), spring (April–June), summer (July–September), and fall (October–December).

Wind

Wind climatologies for the Mariana Archipelago suggest seasonal variability in wind speed and direction (Fig. 3.3.1a). Strong mean winds (8–10 m s^{-1}) were consistently observed across the entire Mariana Archipelago during the fall season. During winter, winds were stronger in the southern portion of this archipelago and progressively weaker in the northern islands. A similar, but weaker, south–north gradient in wind speeds was observed in the spring. During summer, this pattern was reversed with stronger winds in the north and weaker winds in the south. Unlike wind speed, latitudinal gradients in wind direction were not evident, although the direction of the wind changed seasonally. Winds tended to originate from the northeast in the fall and winter, from the east in the spring, and from the east-southeast during the summer.

Figure 3.3.1a. Seasonal wind climatology for (*a*) fall (October–December), (*b*) winter (January–March), (*c*) spring (April–June), and (*d*) summer (July–September), using NASA QuikSCAT scatterometer winds for the Mariana Archipelago (12°–22° N, 140°–150° E). Wind velocities (m s^{-1}) are color coded and arrows indicate relative magnitude and direction. Climatologies were produced using data from 1997 to 2007.

Ocean Surface Currents

The principal ocean current influencing the Mariana Archipelago is the westward-flowing North Equatorial Current (NEC). Based on seasonal climatologies of ocean surface current, the NEC was stronger in the southern islands than in the north-ernmost islands, although the strength of this current varied seasonally and was highly dependent upon latitude within this island chain (Fig. 3.3.1b). Across the Mariana Archipelago, the strongest surface current occurred during the fall, with the southern islands experiencing mean flow speeds of 0.20–0.25 m s^{-1}. Surface currents gradually weakened north of Saipan, with speeds at Asuncion, Maug, and Farallon de Pajaros less than half (0.05–0.10 m s^{-1}) of the speeds experienced in the southern islands. Surface currents were slightly weaker in the winter and spring than in the fall, although a similar

north–south gradient existed. The weakest surface currents across the Mariana Archipelago occurred during the summer; however, surface currents south of Tinian were stronger during this season than currents in the northernmost islands during any season. Additionally, in the summer, a weak current reversal (eastward flow) was apparent north of Farallon de Pajaros, and this current may have influenced this island during certain years depending upon interannual variability (Fig. 3.3.1b).

Figure 3.3.1b. Seasonal ocean surface current climatology for (*a*) fall (October–December), (*b*) winter (January–March), (*c*) spring (April–June), and (*d*) summer (July–September) using NOAA's OSCAR (http://www.oscar.noaa.gov/). Current velocities (m s^{-1}) are color coded and arrows indicate relative magnitude and direction. Climatologies were produced using data from 1993 to 2009.

Sea-surface Temperature

Mean seasonal SST climatologies exhibit pronounced seasonal cycles and latitudinal gradients across the Mariana Archipelago (Fig. 3.3.1c). Annual temperature differences across this archipelago were as much as 5°C; warm temperatures (29°C–30°C) were observed during summer months, and cooler temperatures (25°C–27°C) occurred during the winter. During fall, winter, and spring, a pronounced SST gradient occurred with warmer waters to the south and cooler waters to the north. An average 2.5°C difference in SST occurred between the northernmost and southern islands in each of the fall, winter, and spring seasons. This SST gradient weakened and became more diffuse during the summer months as the entire archipelago was bathed in warm surface water characteristic of Western Pacific Warm Pool conditions (Yan et al. 1992).
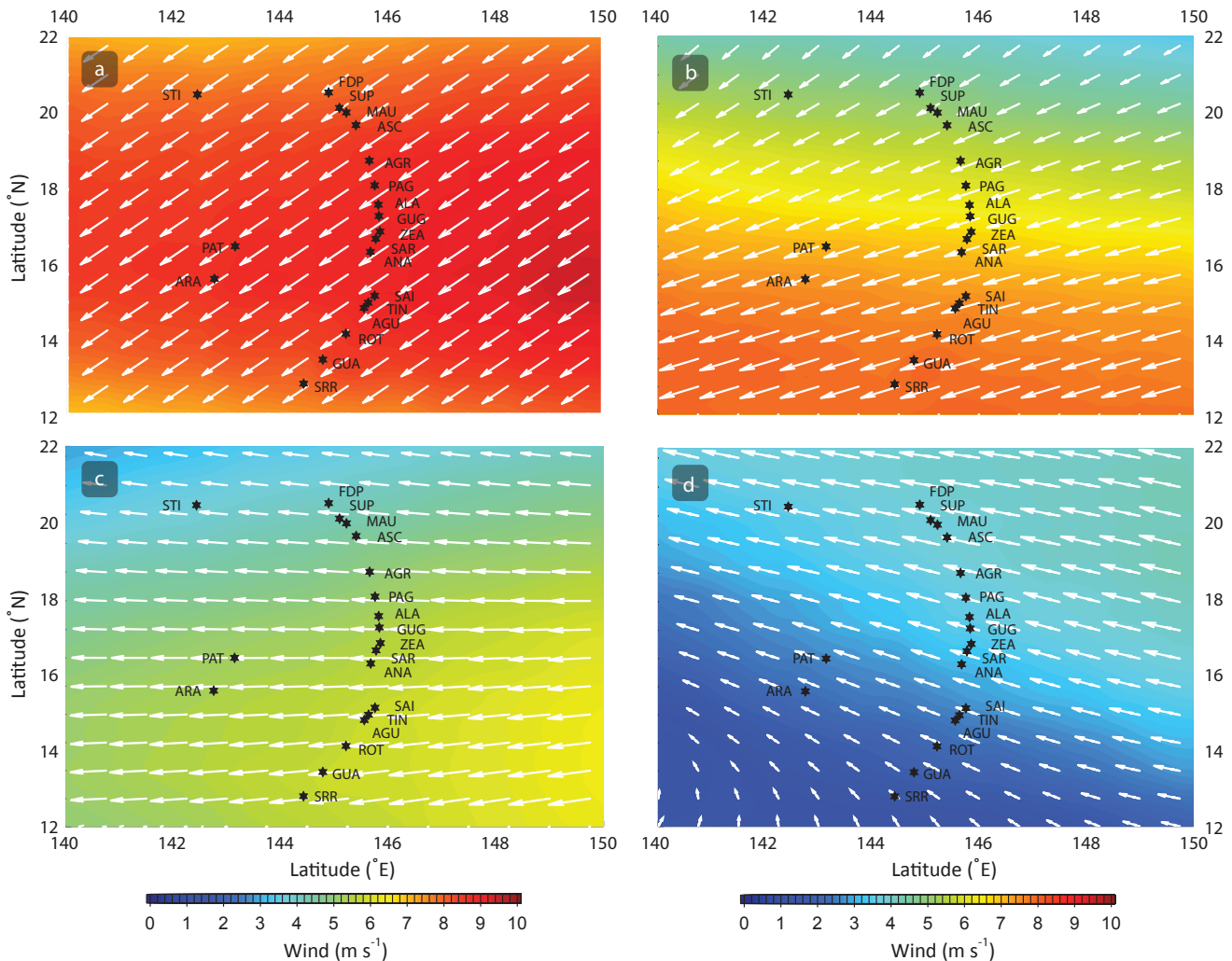
Figure 3.3.1c. Seasonal SST climatology for (*a*) fall (October–December), (*b*) winter (January–March), (*c*) spring (April–June), and (*d*) summer (July–September) in the Mariana Archipelago (12°–22° N, 140°–150° E). Satellite-derived data are from Pathfinder 5.0 SST seasonal climatology from 1982 to 2007 produced by the NOAA National Oceanographic Data Center.

Chlorophyll-a

Mean climatological surface Chl-*a* concentrations show strong seasonal variability in the Mariana Archipelago, with the lowest concentrations occurring in the summer and fall seasons and the highest concentrations observed in the spring and winter (Fig. 3.3.1d). Latitudinal gradients in Chl-*a* levels, with higher concentrations in the north compared to the south, were evident in all 4 seasons, particularly in the winter when Chl-*a* concentrations were 0.4–0.6 µg L^{-1} greater in the northernmost islands than in the southern islands. In general, the southern islands were surrounded by oligotrophic (i.e., nutrient poor) waters throughout the year, while the northernmost islands experienced a much greater seasonal variability. Near Anatahan, during spring and summer, a strong (1 µg L^{-1}) Chl-*a* signal was observed. However, this signal was an artifact of enhanced reflectance as a result of volcanic activity and the combination of smoke and surface ash deposits into the surrounding waters, aliasing ocean color in this area, and was, therefore, not an accurate measure of surface Chl-*a* concentration.

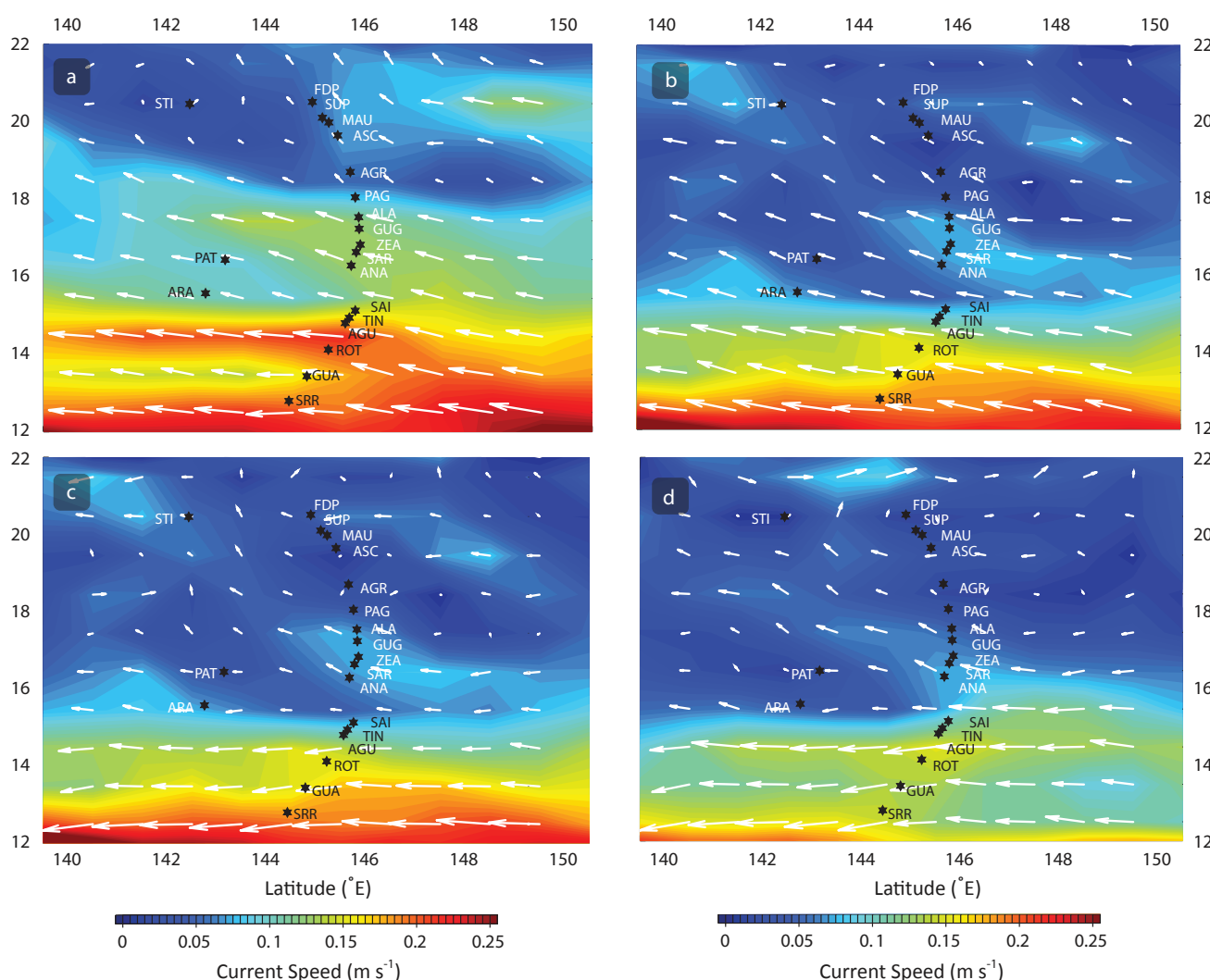**Figure 3.3.1d**. Seasonal Chl-*a* climatology for (*a*) fall (October–December), (*b*) winter (January–March), (*c*) spring (April–June), and (*d*) summer (July–September) from NASA SeaWiFS imagery for the Mariana Archipelago (12°–22° N, 140°–150° E). Climatologies were produced using data from 1997 to 2007.

Precipitation

Mean seasonal precipitation climatologies exhibit pronounced seasonal variability in the Mariana Archipelago, with the lowest rainfall observed during the winter and spring seasons and the highest rainfall observed during the summer and fall (Fig. 3.3.1e). Latitudinal gradients in precipitation, with lower rainfall in the north compared to the south, were evident in all seasons, although the strongest north–south gradient occurred during the summer and fall, when rainfall was ~ 4 mm d^{-1} greater in the southern islands than in the northernmost islands. Over all seasons, the southern islands experienced a minimum of 2 mm d^{-1} in the winter and a maximum of 12 mm d^{-1} in the summer months, while the northernmost islands experienced the same winter minimum and a much lower summer maximum of 8 mm d^{-1}.
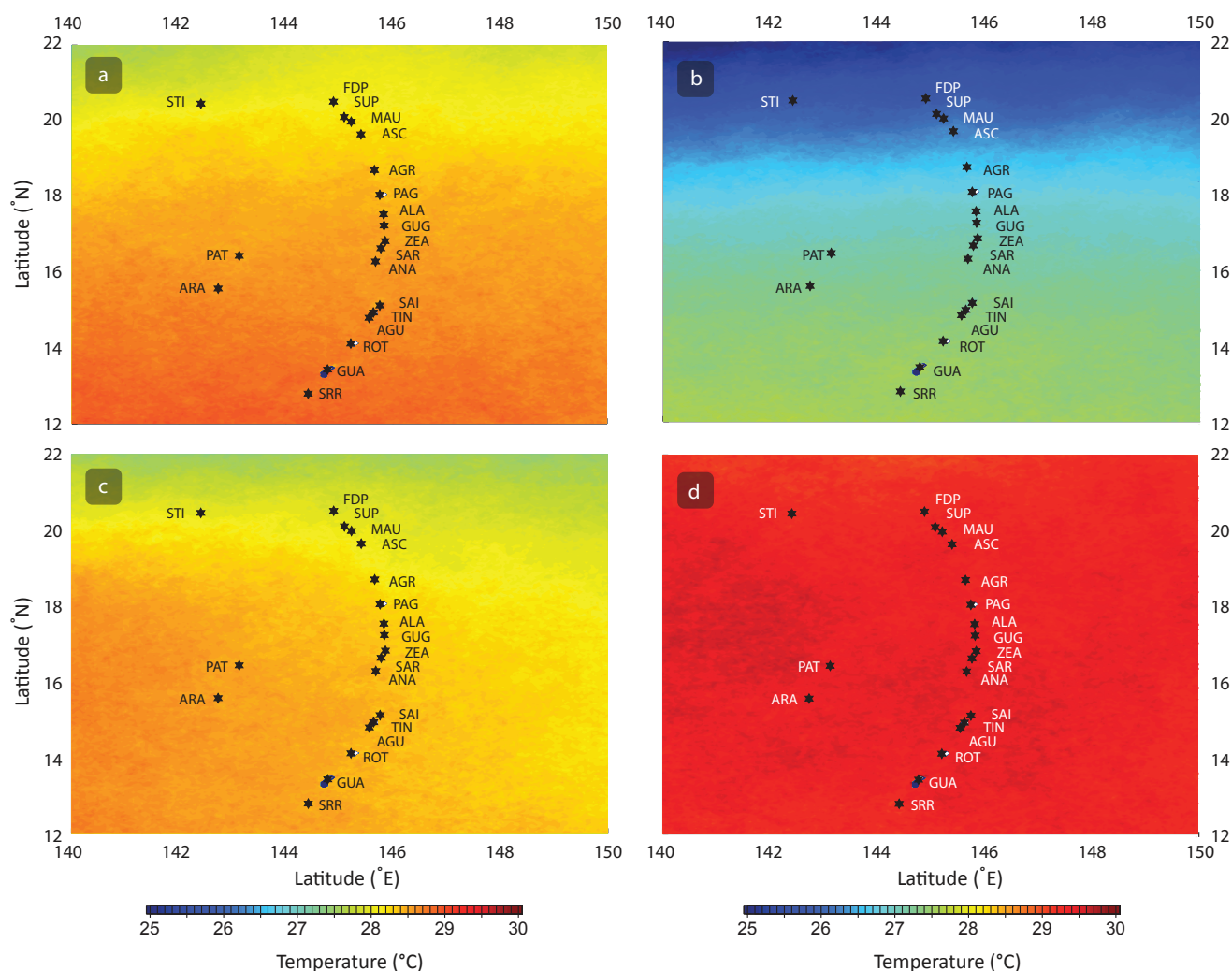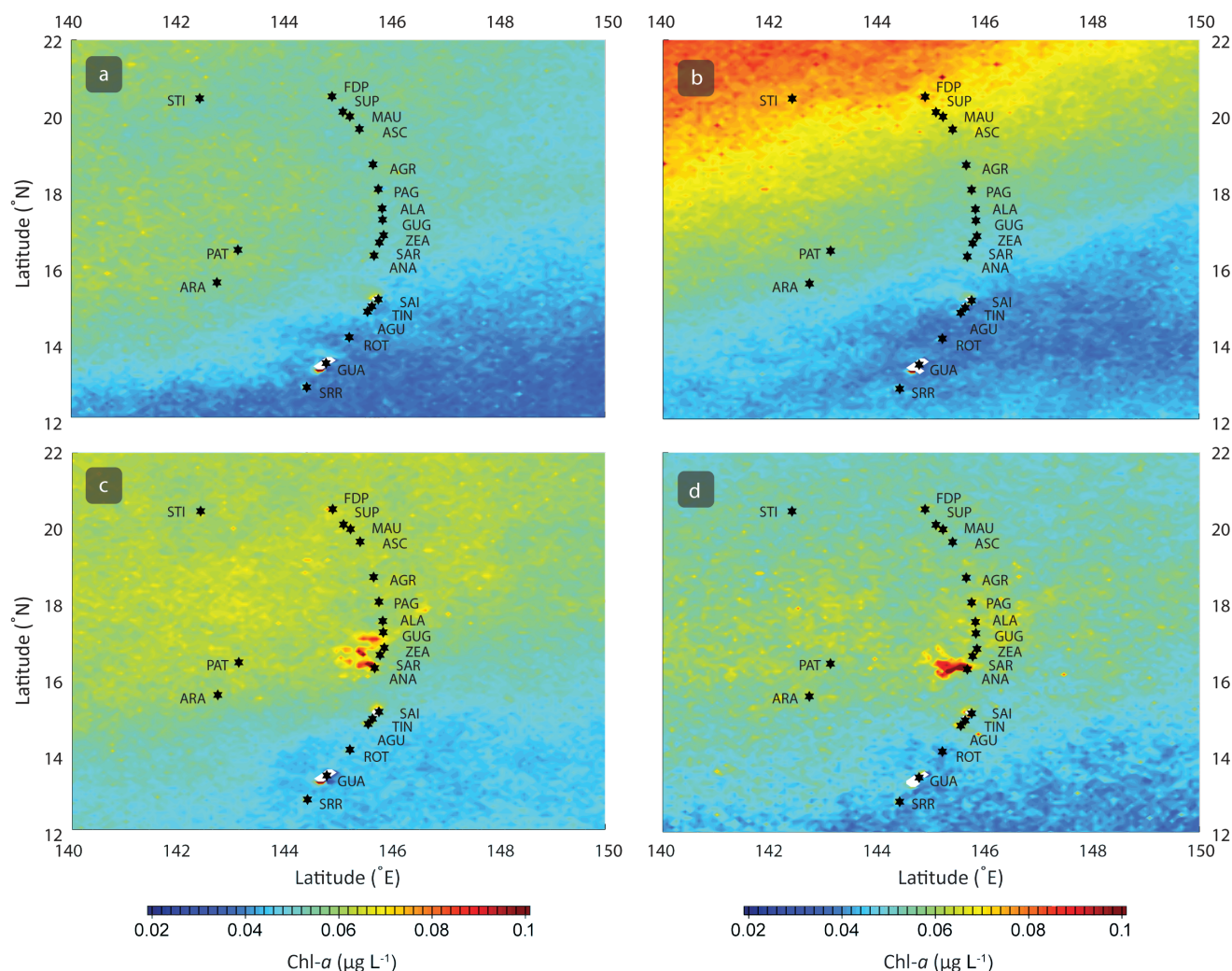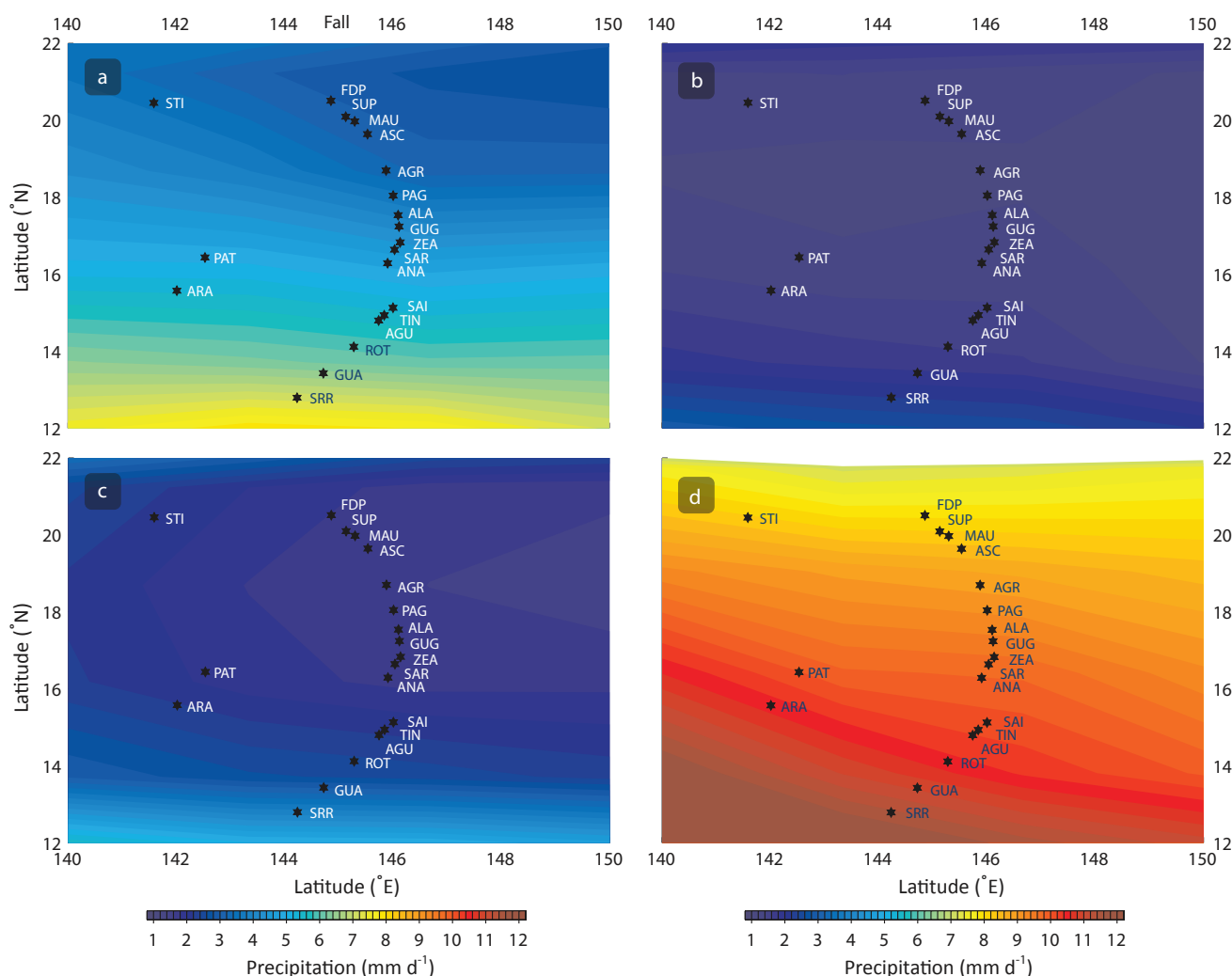
Figure 3.3.1e. Seasonal precipitation climatology for (*a*) fall (October–December), (*b*) winter (January–March), (*c*) spring (April–June), and (*d*) summer (July–September) for the Mariana Archipelago (12°–22° N, 140°–150° E). Climate Prediction Center merged analysis precipitation (CMAP) data are provided by the Physical Sciences Division of the NOAA Earth System Research Laboratory, Boulder, Colo., and are available at http://www.esrl.noaa.gov/psd. Climatologies were produced using data from 1979 to 2010.

Ocean Waves

Annual wave climatologies were derived using the NOAA Wave Watch III model for the period of January 1997 to June 2009 for 4 locations (Maug, Pagan, Saipan, and Guam) spanning the Mariana Archipelago (for information about the Wave Watch III model, see Chapter 2: "Methods and Operational Background," Section 2.3.7: "Satellite Remote Sensing and Ocean Modeling"). These climatologies suggest a consistent wave regime for this island chain (Fig. 3.3.1f). Ambient wave conditions, or conditions that occurred most frequently through the year, were relatively similar across the Mariana Archipelago, with east and northeast exposures experiencing year-round, relatively short-period (8–10 s), low-amplitude (1–2 m) waves. Episodic wave events, in contrast, were wave episodes that occurred irregularly through the year. These waves were generated by storms that were either within close proximity (tens to hundreds of kilometers) or at great distances (hundreds to thousands of kilometers) from the Mariana Archipelago, and they generally had longer periods and higher amplitudes than waves characterized by ambient conditions. Moderate episodic wave events, storm generated but low to moderately energetic, were evenly distributed around each island and across the Mariana Archipelago. These events had waves with periods of 10–16 s and amplitudes of 1–3 m, and they approached these islands ~ 1–5 times each year. Large episodic wave events, storm generated but highly energetic, were characterized by wave periods of 12–16 s and wave amplitudes > 5 m. These events affected the east-southeast (100°–120°) region of Guam and shifted to a southerly direction toward Saipan (120°–150°), Pagan (150°–180°), and Maug (170°–190°). These large, high-energy waves were most likely generated by typhoons. The shift in peak wave direction from the east-southeast to the south from Guam to Maug was likely a result of typhoon paths curving northward as they traveled west after their formation, which typically

occurred southeast of Guam (Fig. 3.3.1g). Although these large wave events occurred only a few times a year, they likely affected the coral reef communities of the Mariana Archipelago.
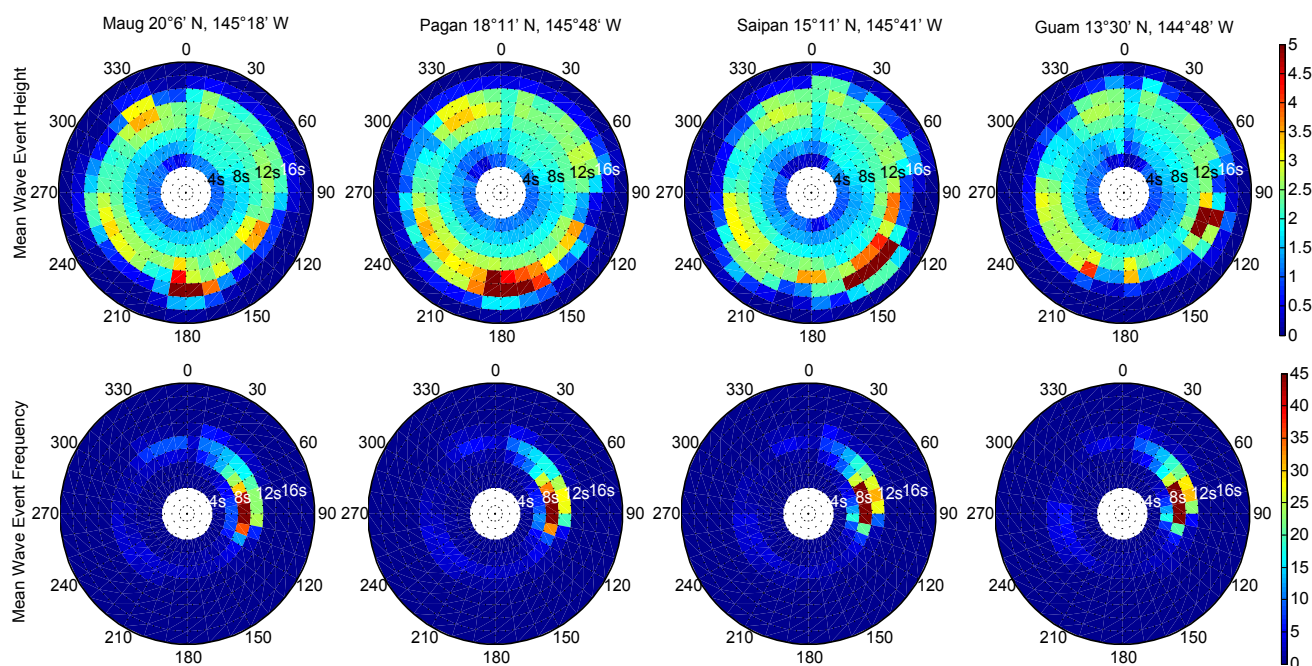
Figure 3.3.1f. Annual event climatology for wave height, direction, and period derived from NOAA Wave Watch III computations at 4-h time steps at Maug (20°6′ N, 145°18′ W), Pagan (18°11′ N, 145°48′ W), Saipan (15°11′ N, 145°41′ W), and Guam (13°30′ N, 144°48′ W) from January 1997 to June 2009. Mean annual wave event height (*top*), indicated by color scale, is represented in given directional and period bins (e.g., an average wave event at Maug with a period of 14–16 s from 180° had a height of 5 m). Mean annual frequency (likelihood) of occurrence (*bottom*), indicated by color scale, is represented in days per year (e.g., a 2-m wave with an 8-s period from 90° occurred on average 45 days a year at Maug).
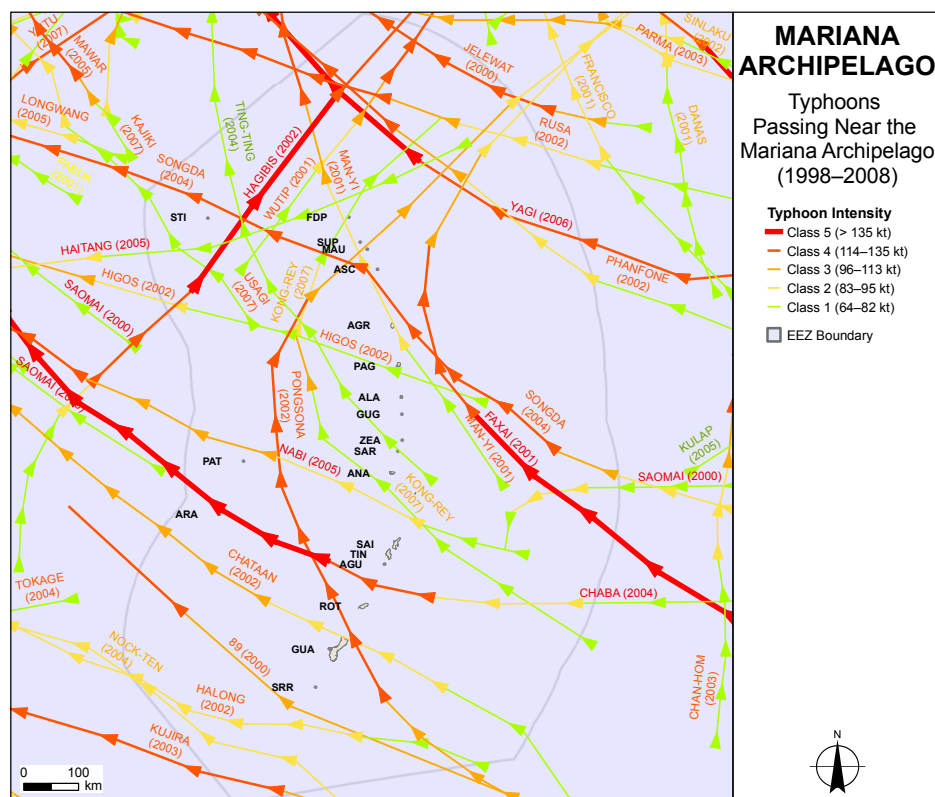
Figure 3.3.1g. Path and intensity of typhoons passing near or across the Mariana Archipelago from 1998 to 2008.

3.3.2 Time-series Observations

In this section, time-series data derived from in situ and satellite remote-sensing observations were used to examine seasonal-to-interannual variability and latitudinal gradients of ecologically significant environmental properties, including wind, surface currents, SST, and Chl-*a* and nutrient concentrations, across the Mariana Archipelago.

Time-series observations of Chl-*a* concentrations, east–west surface currents, and SST from the northernmost, central, and southern islands show distinct latitudinal differences and coupled physical and biological oceanographic variability (Fig. 3.3.2a). Over the 10-year period from 1998 to 2008, Chl-*a* levels were highly variable in each of the 3 island groups; however, the extent of variability, seasonal periodicity, and interannual fluctuations were different for each group (Fig. 3.3.2a, top panel). The time series for the northernmost islands shows relatively high Chl-*a* values and suggests regular seasonal periodicity, with a peak of 0.07–0.09 µg L^{-1} in surface concentrations of Chl-*a* in the winter and a long-term mean of 0.061 µg L^{-1}. The central islands exhibited less seasonal periodicity but more interannual variability than did the northernmost islands, with seasonal peaks in a range of 0.06–0.11 µg L^{-1} during the winter–spring period and a long-term mean of 0.058 µg L^{-1}. Chl-*a* values from May 2003 were removed from the time series because of atmospheric effects from an eruption of Anatahan. The largest peaks (seen in 1998, 2003, and 2005) in the central islands also may have been associated with volcanic activity at Anatahan. The southern islands were characterized by low surface concentrations of Chl-*a* (< 0.05 µg L^{-1}) and moderate periodicity, as seasonal minima tended to occur during the fall–winter period, and a long-term mean of 0.043 µg L^{-1}. Year-to-year differences were observed in the southern islands, although not to the extent seen in the central and northernmost islands, as the range in observed Chl-*a* concentration was relatively small.

Ocean surface currents (east–west only) over the same 10-year period were highly variable from year to year with no clear seasonal periodicity (Fig. 3.3.2a, middle panel). Surface currents in the northernmost islands were relatively weak (magnitude < 0.15 m s^{-1}) and oscillated between eastward (positive) and westward (negative) flows. Pronounced peaks of eastward flow were observed in this time series, although the timing of these peaks varied by year. The central islands experienced increased westward current and increased seasonal periodicity; however, interannual variability was clearly present. Seasonal peaks in westward flow occurred during the fall–winter period, and increased eastward flow was observed during the spring–summer period. The southern islands, in contrast to the central and northernmost islands, were characterized by year-round westward flow, with seasonal increases occurring in the fall–winter transition, particularly from 2003 to 2007. This observation is consistent with the seasonal climatology data, which show a stronger NEC in the southern islands, versus the other island groups, with a seasonal strengthening during the winter months (Fig 3.3.1b).

In contrast to patterns seen for Chl-*a* concentrations and ocean surface currents, SST data show strong seasonal periodicity in all 3 island groups, with the range of variability dependent upon latitude (Fig. 3.3.2a, bottom panel). A seasonal

Figure 3.3.2a. Time series of satellite-derived (*top)* Chl-*a* concentration (SeaWIFS), (*middle*) East–West current (OSCAR), and (*bottom*) SST (Pathfinder) from 3 island groups in the Mariana Archipelago, using a box (1° × 1°) centered on 20° N, 144°48' E for the northernmost islands, 16°30' N, 145° E for the central islands, and 13° N, 145° E for the southern islands. Note: Chl-*a* data from May 2003 were removed from this time series for the central islands because of an eruption of Anatahan.
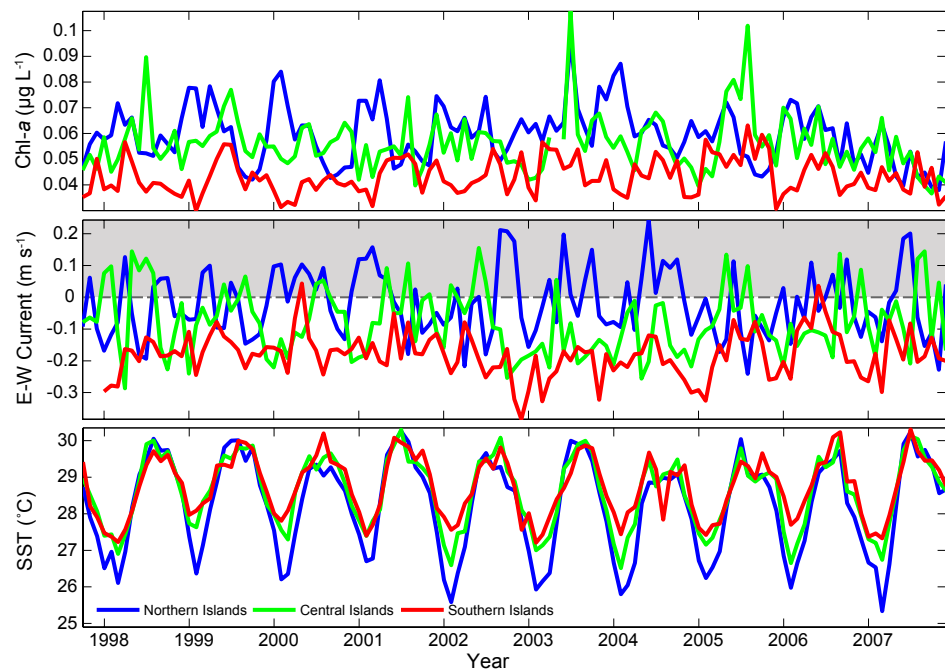
maximum in SST was seen in each island group in the summer and a seasonal minimum in the winter. The peaks in SST (~ 30°C) were generally the same for each of the island groups; however, the seasonal minimum was colder (~ 26°C) in the northernmost islands than the minima for the central (~ 27°C) and southern (~ 27.5°C) islands. Interannual forcing is clearly evident in each of the SST time series. Year-to-year temperature variability was greatest in winter in all island groups, with the largest interannual variability observed in the northernmost islands.

Although it is difficult to discern direct correlations between Chl-*a* concentrations, surface currents, and SST on monthly to seasonal time scales, patterns do emerge when analyzing the entire 10-year time series. In the northernmost islands, Chl-*a* concentrations reached their highest levels concurrently with peaks in eastward surface current in 1999, 2000, and 2001 and, to a lesser extent, in 2005 and 2006. These concomitant peaks in Chl-*a* values and surface current tended to occur in the winter, when temperatures were seasonally low. The central islands showed less concurrence, compared to the other island groups, although, in 1998 and 2005, strong peaks in Chl-*a* concentrations were observed during the highest points in eastward flow.

CRED's SST buoys moored at Maug, Pagan, and Guam collected and telemetered in situ, high-resolution, nearshore temperature time-series data that, when combined with remotely sensed, satellite-derived (Pathfinder) SST information, provide a valuable context for evaluating island-scale temperature fluctuations and latitudinal differences.

Throughout the 4-year observational time series from 2003 to 2007, in situ and remotely sensed SST followed similar seasonal patterns, with minimum temperatures observed in January–March and maximum temperatures recorded in July–September (Fig. 3.3.2b). However, in situ SST at all locations at various times showed large deviations from remotely sensed temperatures. During the winter and spring of both 2004 and 2005, for example, in situ temperature at Maug was almost 1°C colder than SST observed via satellite. Additionally, in situ SST at Maug and Pagan contemporaneously dropped 1.5°C–2°C, then sharply rose 2°C–3°C in the summer of 2004. A 1°C change in satellite SST was recorded during that same time frame, as temperatures changed too rapidly for remotely sensed data to match in situ data.
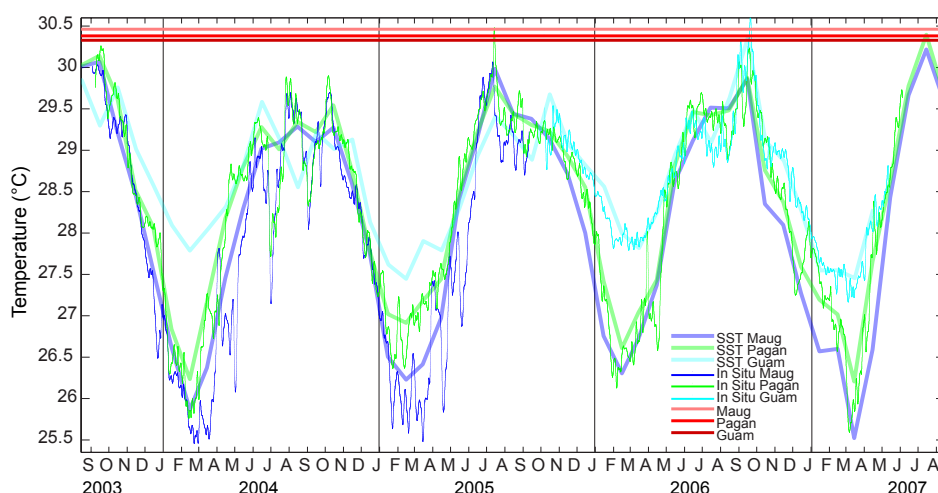
Figure 3.3.2b. Time series of satellite-derived SST (Pathfinder) and in situ SST (when available) from Maug, Pagan, and Guam. The horizontal red lines indicate the coral bleaching threshold, defined as 1°C above the monthly maximum climatological mean, at each island.

Hydrographic Data

Spatial hydrographic surveys—which collect conductivity, temperature, and depth (CTD), oxygen, and fluorescence profiles, as well as in situ information on water-quality conditions—enable assessment of subsurface water column properties pertinent to coral reef communities. CTD and water-quality information presented in this section were averaged by individual island, allowing for archipelagic comparison of oceanographic information, and separated by survey year, in an effort to remove confounding issues associated with seasonal differences in MARAMP survey years (MARAMP 2005 surveys were conducted in September and October and MARAMP 2007 surveys occurred in May and June).

CTD profiles obtained during MARAMP 2005 and 2007 suggest distinct latitudinal gradients in water properties. In 2005, temperatures were uniform and the water well mixed in the upper part of the water column at depths of 50–75 m around all islands in the Mariana Archipelago (Fig. 3.3.2c). Below this depth range, waters around most islands had similar rapid decreases in temperature with depth, but waters around Guguan and Pagan cooled more slowly with depth. At a 200-m

depth, a clear separation of temperatures was found between all islands, and below 300 m, around the northernmost islands, particularly Farallon de Pajaros and Asuncion, recorded temperatures were ~ 5°C warmer than temperatures observed in rest of this island chain.

Salinity profiles from MARAMP 2005 were highly variable between islands. The subsurface salinity maximum was recorded at a depth of 150 m for waters around all islands except Guguan and Pagan, where the maximum occurred at a depth of ~ 220 m. Below 200 m, the waters around all islands showed a separation of salinity values, with the lowest salinity levels recorded in the southern islands.

Oxygen saturation values, as with temperatures, were relatively uniform in 2005 around all islands in the upper water column to a depth of 100 m. With increasing depth, waters around Farallon de Pajaros and Asuncion retained high levels of oxygen saturation, while saturation in waters around the other islands decreased with depth. Below 300 m, a substantial separation of oxygen saturation profiles was recorded, with waters around the southern islands having the lowest recorded levels to a depth of 500 m.

Fluorometry profiles from the water column around each of island in 2005 reveal a wide range of values in the upper water column to a depth of 100 m, with the greatest values recorded around Guam and Aguijan and the lowest values recorded around Farallon de Pajaros and Asuncion. High fluorescence values suggest enhanced productivity. Taking into account human population and island size, island-based sources of nutrients likely entered the nearshore waters of Guam, enhancing surface productivity. Nutrient and Chl-*a* concentrations are presented later in this section.

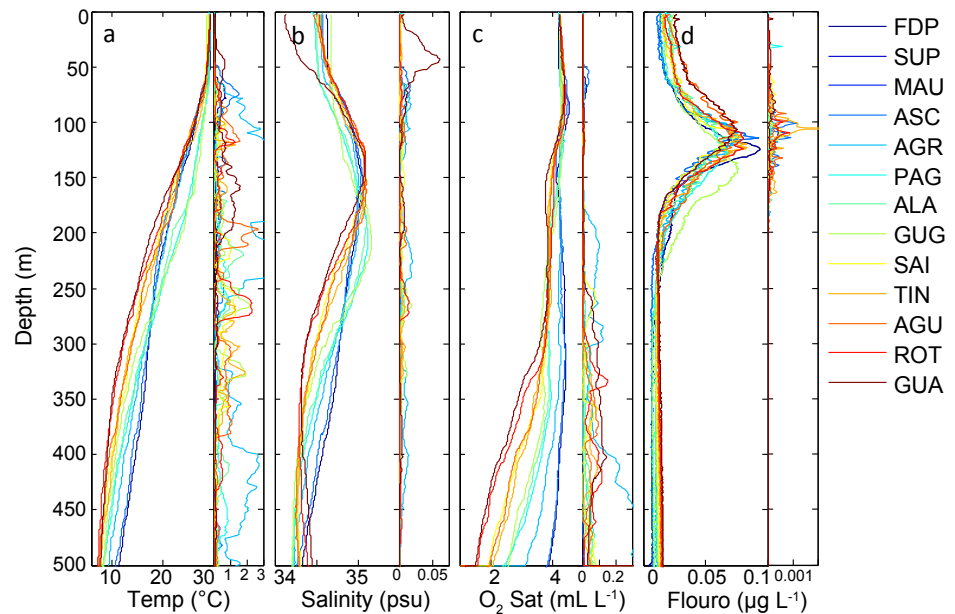**Figure 3.3.2c.** Values of (*a*) temperature, (*b*) salinity, (*c*) oxygen saturation, and (*d*) fluorometry from shipboard (depths to 500 m) CTD casts conducted in the Mariana Archipelago during MARAMP 2005. Data were averaged by island with calculated variance shown at the right of each panel.

CTD data obtained during MARAMP 2007 reveal distinct north–south differences in vertical water properties. Waters around Maug and Farallon de Pajaros were ~ 5°C colder in the upper water column to a depth of 50 m than in similar waters around all other islands (Fig. 3.3.2d). The waters at depths of 50–200 m in the northernmost islands were distinctly colder than waters at this depth range in the rest of the Mariana Archipelago, although high variance was observed in the entire water column around Agrihan for reasons that are presently unknown. This north–south temperature orientation abruptly switched at depths > 250 m, where waters of the southernmost islands were colder to depths of 500 m.

Salinity profiles from MARAMP 2007 were far more dispersed and clearly latitudinally oriented in the upper water column compared to temperature profiles, with the lowest salinities recorded in the southern islands and the highest in waters around the northernmost islands. As with temperature, salinity profiles from the water column around Agrihan exhibited a high degree of variance.

Oxygen saturation around all islands was low in the upper water column to the surface in 2007, while, below a depth of 10 m, values were generally higher in waters at the northernmost islands than in waters at the southern islands. This north–south separation continues with increasing depth.
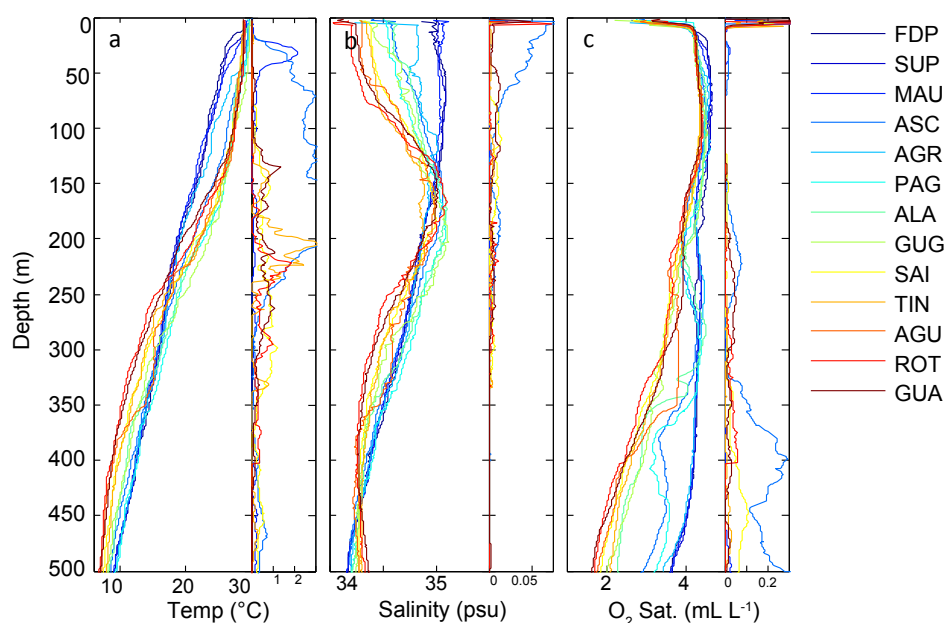
Figure 3.3.2d. Values of (*a*) temperature, (*b*) salinity, and (*c*) oxygen saturation from shipboard (depths to 500 m) CTD casts conducted in the Mariana Archipelago during MARAMP 2007. Data were averaged by island with calculated variance shown at the right of each panel.

Water Quality

In situ observations of water-quality conditions at each island enables comparisons of Chl-*a* and nutrient concentrations across the Mariana Archipelago. Results from nearshore water samples collected during MARAMP 2005 were highly variable with no distinct geographic patterns across this island chain (Fig. 3.3.2e). Silicate (Si[OH]$_4$) concentrations were greatest in waters at Pagan, Guam, Anatahan, and Maug, while nitrate (NO$_3^-$), concentrations were generally low in waters at all islands except for Tinian and Rota. Nitrite (NO$_2^-$) values were similarly low throughout the Mariana Archipelago, except at Guam, where much higher values were observed. With regards to phosphate (PO$_4^{3-}$), waters at Anatahan had nearly twice the concentration recorded at any other island, likely owing to the deposition of ash and other volcanic material resulting from eruptions at this island prior to the MARAMP 2005 surveys.

Figure 3.3.2e. In situ concentrations of Chl-*a*, phosphate (PO$_4^{3-}$), silicate (Si[OH]$_4$), nitrate (NO$_3^-$), and nitrite (NO$_2^-$) from nearshore (depths ≤ 30 m) water samples collected during MARAMP 2005. Data represent averages from all samples and all depths at each island. See Chapter 2: "Methods and Operational Background," Section 2.3.3: "Nearshore Spatial Surveys" for data acquisition and processing protocols, and see island chapters for water sample locations. Error bars indicate the standard error (± 1 SE) of the mean.

In contrast to results from MARAMP 2005, which occurred in September and October, data from nearshore water samples collected during MARAMP 2007, which occurred in May and June, suggest distinct patterns in Chl-*a* and nutrient concentrations across the Mariana Archipelago (Fig. 3.3.2f). Island size appeared to heavily influence Chl-*a* concentrations, as the highest levels in 2007 were recorded at 5 of the islands with the largest land areas (Guam, Saipan, Tinian, Pagan, and Anatahan). Phosphate concentrations showed a clear north–south gradient, with the lowest values recorded in the northernmost islands and the highest in the southern islands. Silicate (Si[OH]$_4$) concentrations were greatest in waters in the central islands, relatively high in the northernmost islands, and lowest in the southern islands. Concentrations of nitrate (NO$_3^-$)

were highest in waters at Guam but decreased rapidly moving northward with each subsequent island in the southern island group, while relatively high concentrations were observed in waters at Sarigan and most of the other central islands. Nitrite (NO_2^-) values were greatest in waters at Asuncion and Pagan.

Figure 3.3.2f. In situ concentrations of Chl-*a*, phosphate (PO_4^{3-}), silicate ($Si[OH]_4$), nitrate (NO_3^-), and nitrite (NO_2^-) from nearshore (depths ≤ 30 m) water samples collected during MARAMP 2007. Data represent averages from all samples and all depths at each island. See Chapter 2: "Methods and Operational Background," Section 2.3.3: "Nearshore Spatial Surveys" for data acquisition and processing protocols, and see island chapters for water sample locations. Error bars indicate the standard error (± 1 SE) of the mean.
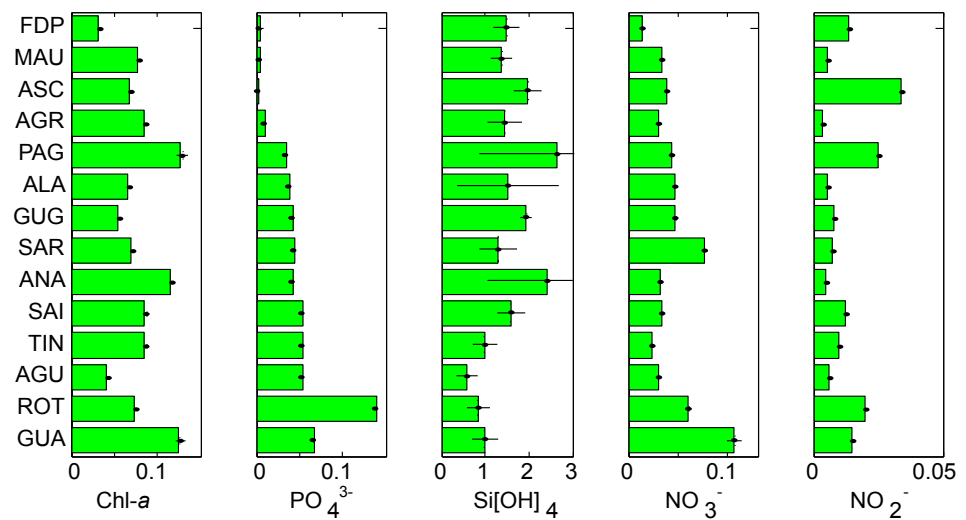
Results from shipboard water samples collected to depths of 250 m during MARAMP 2007 show latitudinal patterns similar to the ones observed in nearshore sample data for each of the measured parameters. In general, the northernmost and southern islands had moderate to high concentrations of all parameters measured, while the central islands had moderate to low concentrations (Fig. 3.3.2g). Guam had the greatest concentrations of nutrients in the Mariana Archipelago, a result that is not surprising given the population density and size of that island. An obvious exception to these observed trends occurred at Guguan. Despite its location in the middle of the Mariana Arc, Guguan had some of the highest recorded concentrations for all parameters measured. The cause of anomalously high nutrient and Chl-*a* concentrations there is not clear; however, it is possible that a mesoscale oceanographic feature (e.g., mid-ocean eddy) was present during sampling, causing a vertical flux of nutrients and increased productivity in the vicinity of Guguan. This notion is supported by results from nearshore water samples collected in 2007 at Guguan (Fig. 3.3.2f), where nutrient and Chl-*a* concentrations were comparable to levels found at islands near Guguan. If the anomalously high concentrations recorded from the shipboard samples were a result of terrigenous input, groundwater discharge, a locally generated oceanographic phenomenon (e.g., internal tides), or some other island-based source, then data from nearshore water samples also would show anomalously high values. This clear disparity between these 2 concomitant data sets is paradoxical but not improbable, as transient mid-ocean eddies are common in the world's oceans and can lead to increased nutrients and enhanced surface productivity.
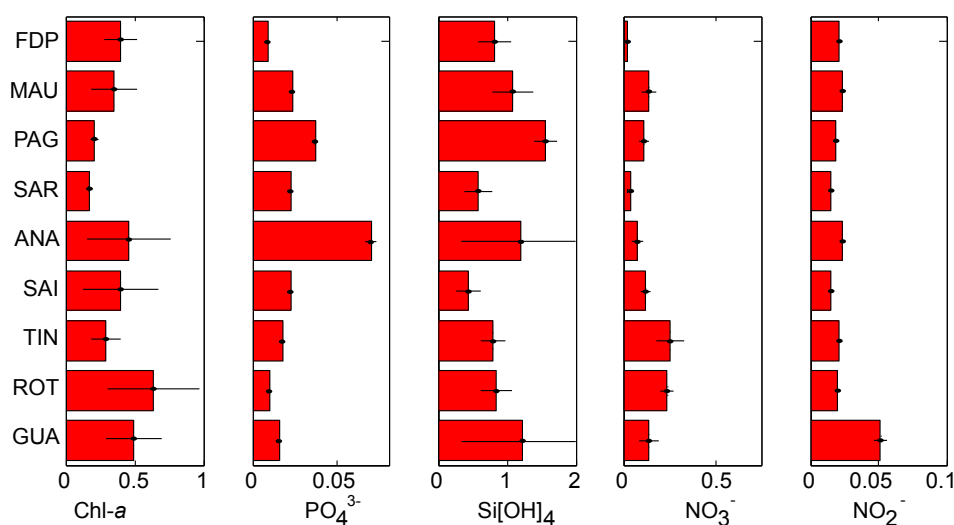
Figure 3.3.2g. In situ concentrations of Chl-*a*, phosphate (PO_4^{3-}), silicate ($Si[OH]_4$), nitrate (NO_3^-), and nitrite (NO_2^-) from shipboard (depths < 250 m) water samples collected during MARAMP 2007. Data represent averages from all samples and all depths at each island or bank. See Chapter 2: "Methods and Operational Background," Section 2.3.2: "Shipboard Surveys" for data acquisition and processing protocols. Error bars indicate the standard error (± 1 SE) of the mean.
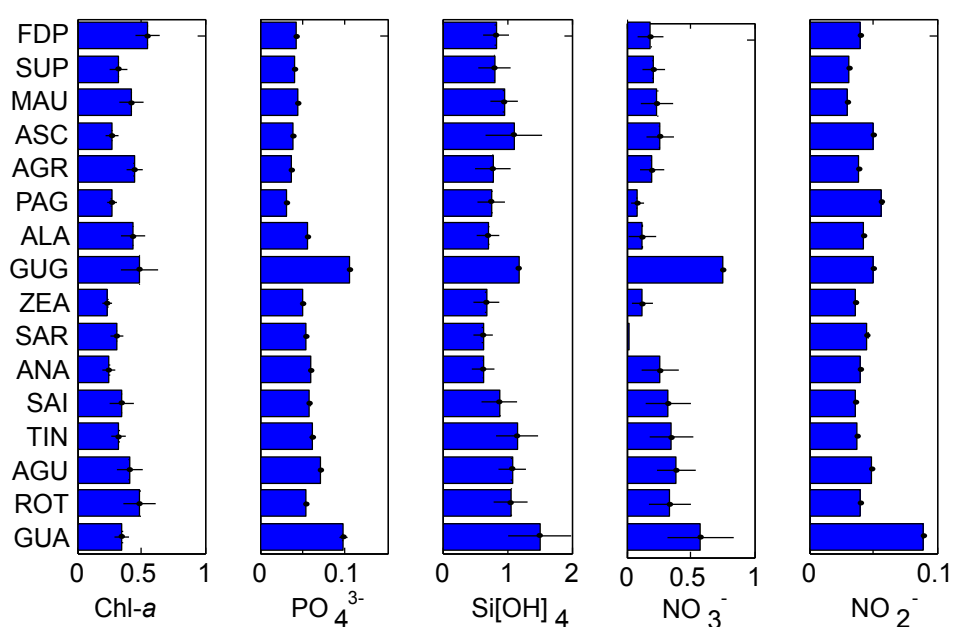
3.4　Corals and Coral Disease

3.4.1　Coral Surveys

Coral Cover

Archipelago-wide, estimates of mean cover of live hard corals from towed-diver benthic surveys of forereef habitats were highly variable without obvious spatial or temporal patterns. Looking at results of REA and towed-diver surveys just for 2007, however, suggests that cover levels generally were lower at the southern islands than at the northern islands (Fig. 3.4.1a). Compared to results at other islands in the Mariana Archipelago, the highest level of coral cover was recorded consistently at Maug during MARAMP 2003, 2005, and 2007, with overall means of 27% (SE 1.4), 21% (SE 1.7), and 26% (SE 1.6). Guam, along with Maug, had the highest coral cover recorded at an island in 2005, with an overall mean of 23% (SE 1.2), but observed coral cover in 2007 was lower there, with an islandwide mean of 12% (SE 0.8) (Fig. 3.4.1a). The next-greatest values of coral cover in 2003 were observed at Guguan and Saipan, with overall means of 23% (SE 1.9) and 21% (SE 2.3); Guguan, along with Maug, had the highest coral cover recorded in this archipelago in 2007, with an islandwide mean of 27% (SE 2). Some of the lowest values of coral cover in the Mariana Archipelago were recorded consistently in the 3 MARAMP survey years around Rota, with overall means ranging from 4% (SE 1) to 9% (SE 1.1), and Farallon de Pajaros, with islandwide means ranging from 5% (SE 0.6) to 10% (SE 0.9). Low coral cover was also noted at Anatahan, with an islandwide mean of 8% (SE 0.6) in 2003, the only year in which MARAMP surveys were conducted at this island. Intermediate levels of coral cover were observed at Aguijan, Sarigan, Agrihan, and Asuncion in the 3 survey years, with overall means ranging from 12% (SE 1.2) to 18% (SE 2). Declines in overall mean coral cover were estimated for Saipan between 2003 and 2007 and for Guam between 2005 and 2007, and increases in islandwide mean coral cover were observed at Alamagan and Pagan between 2005 and 2007.

For the remote banks of the West Mariana Ridge, estimates of coral cover from towed-diver surveys were high: 55% (SE 2.7) at Stingray Shoal in 2003 and 25% (SE 1.4) at Pathfinder Reef in 2005 (Fig. 3.4.1a). A 50% change in estimated mean coral cover was observed at Arakane Reef from 24% (SE 1.1) in 2003 to 12% (SE 1.6) in 2005 (survey effort there included 53 survey segments in 2003 versus 30 segments in 2005). Surveys at Santa Rosa Reef, located south of Guam, and at Tatsumi Reef, located south of Tinian, revealed the lowest values of coral cover recorded in the Mariana Archipelago in 2003, with overall means of 7% (SE 0.9) and 8% (SE 1.8). No towed-diver surveys were conducted on the remote and offshore banks in 2007.

In addition to observations of live coral cover, estimates of stressed-coral cover, including corals that were fully bleached (white), pale or discolored, malformed, or stricken with tumors, were recorded as part of towed-diver surveys conducted on forereef habitats during MARAMP 2005 and 2007 (see Chapter 2: "Methods and Operational Background," Section 2.4.5: "Corals and Coral Disease"). In 2005 and 2007, islandwide mean stressed-coral cover ranged from < 1% to 8%. The highest level in 2005 of 5% was observed at both Agrihan (SE 2.4) and Guam (SE 0.6), and the greatest values in 2007 were recorded at Aguijan, Saipan, and Guam with overall means of 8% (SE 1.1), 6% (SE 0.6), and 5% (SE 0.6; Fig. 3.4.1a). Few corals appeared stressed at Guguan and Sarigan, where islandwide mean values were < 1% in both years. Between surveys in 2005 and 2007, overall mean stressed-coral cover increased considerably around 3 southern islands: Aguijan, Saipan, and Tinian. Estimates for Agrihan decreased during that same time period. Observations from towed-diver surveys suggest that the relatively high stressed-coral cover at certain islands was likely a consequence of the high abundance of the crown-of-thorns seastar (*Acanthaster planci*). For more information on densities of the crown-of-thorns seastar, see Section 3.6: "Benthic Macroinvertebrates."

Results from REA benthic surveys, using the line-point-intercept method on forereef habitats in 2007, suggest that mean cover of live hard corals was moderate and similar among the 4 populated, southern islands of the Mariana Archipelago. Conversely, coral cover was more variable among the younger, mostly uninhabited, volcanic, northern islands, where both the highest and the lowest cover values for this archipelago were recorded. The greatest level of coral cover was recorded at Maug, with an overall sample mean of 34.1% (SE 5.7) and high cover of ~ 70% found in some areas, including the *Porites rus* observed inside the caldera off East Island. The next-greatest levels were documented at Agrihan, Alamagan, and Sarigan with overall sample means of 30.7% (SE 6.6), 23.5% (SE 5), and 21.2% (SE 6.9). The lowest overall sample mean for live coral cover from REA surveys in 2007 was observed at Farallon de Pajaros, with 3.6% (SE 0.7), and the next lowest value of 7.8% was estimated at a single REA site at Aguijan. Among the northern islands, the next lowest overall sample means of 10.6% (SE 1.7) and 15.4% (SE 3.5) were recorded at Pagan and Guguan. At all other islands surveyed,

overall sample means ranged from 11.2% to 16.2%. In relatively close agreement with these REA values, islandwide mean coral cover from towed-diver surveys conducted in 2007 was 26% (SE 1.6) around Maug and 5% (SE 0.6) around Farallon de Pajaros and ranged from 10% (SE 0.7) to 16% (SE 1.3) around Guam, Saipan, Pagan, and Asuncion (Fig. 3.4.1a).

Figure 3.4.1a. Spatial and temporal comparison of mean cover (%) of live and stressed hard corals from REA and towed-diver benthic surveys of forereef habitats conducted in the Mariana Archipelago during MARAMP 2003, 2005, and 2007. Surveys of stressed-coral cover were not conducted in 2003. Error bars indicate the standard error (± 1 SE) of the mean.

order of taxa by abundance varied among islands and MARAMP survey periods, although *Pocillopora, Pavona, Porites, Astreopora*, and *Favia* generally were the most numerically abundant genera. Some genera, like *Porites* and *Leptastrea*, were more numerically abundant on the forereefs of the southern islands, while other genera, such as *Pocillopora* and *Pavona*, were more numerically abundant on the forereefs of the northern islands. Environmental parameters, such as salinity, wave exposure, and volcanic activity, appear to be important determinants of coral community distribution and diversity in the Mariana Archipelago (Houk and Starmer 2010). In each survey year, the "Other" category made up the largest part of the coral community at most islands, contributing more than 20% of the relative abundance at an island. This category is composed of an assortment of taxa that individually accounted for < 2% of the corals enumerated during REA benthic surveys.

Figure 3.4.1c. Relative abundance of coral genera from REA benthic surveys of forereef habitats conducted in the Mariana Archipelago during MARAMP 2003, 2005, and 2007.
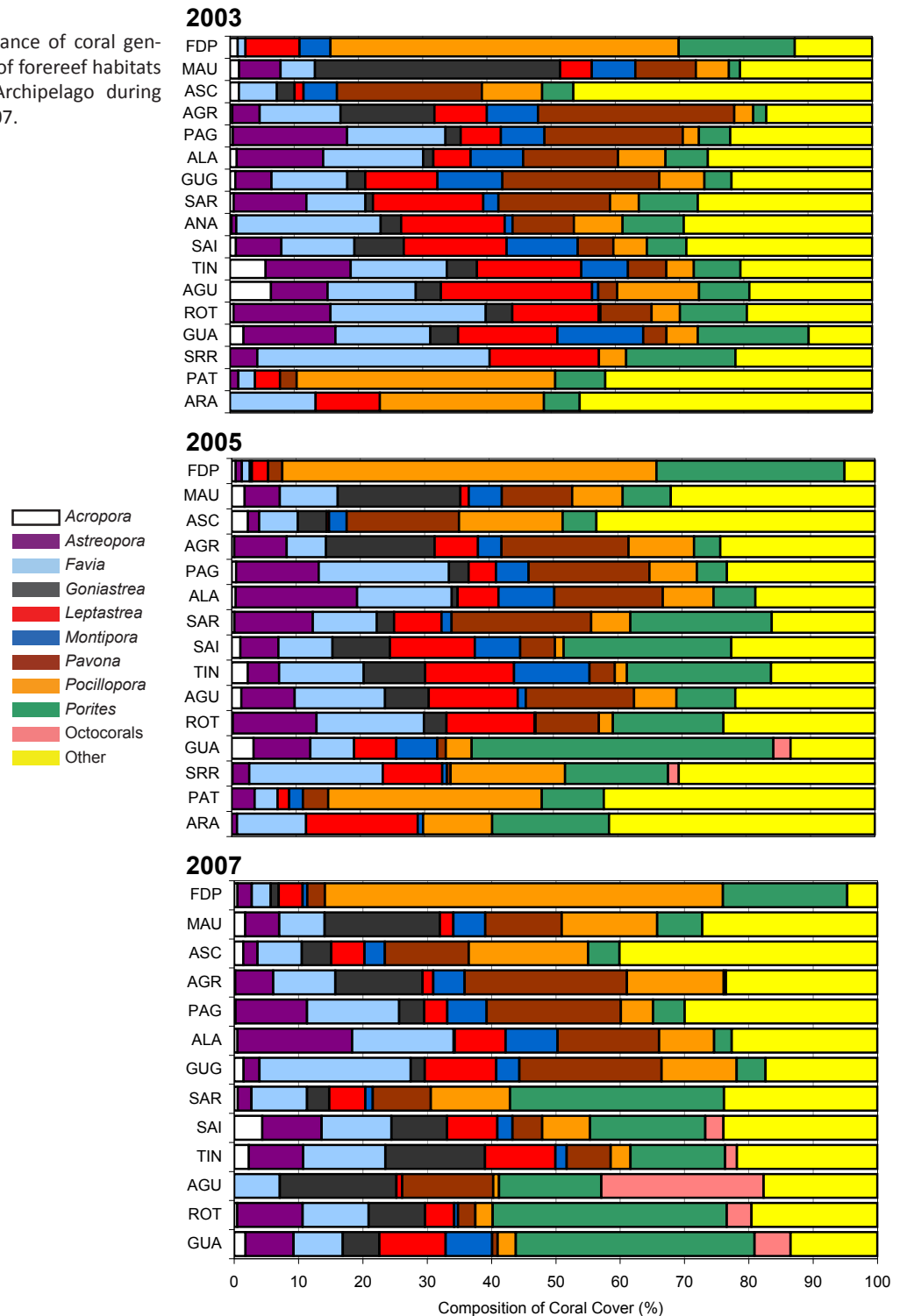
Coral Colony Density and Size-class Distribution

REA benthic surveys were conducted to determine colony density and size-class distribution of hard corals in forereef habitats across the Mariana Archipelago during MARAMP 2007. Two different protocols were implemented to census corals, and islandwide patterns in colony density reflect the intrinsic differences between these methods: two belt transects (25×1 m) were surveyed at 5 southern islands and 16 haphazardly placed quadrats (50×50 cm) were surveyed at the northern islands (see Chapter 2: "Methods and Operational Background, Section 2.4.5: "Corals and Coral Disease"). These methodological disparities preclude quantitative comparisons among islands; nonetheless, regional trends involving all survey sites can be considered.

Among the southern islands, Tinian and Guam in 2007 had the highest coral-colony densities with overall sample means of 6.7 colonies m^{-2} (SE 1) and 6.2 colonies m^{-2} (SE 0.7), while the other 3 southern islands that were surveyed all had overall sample means of ~ 4 colonies m^{-2} (Fig. 3.4.1d). Although elevated colony density can be the result of sexual and asexual reproduction, site-specific differences in reef physiography and biological assemblages may also contribute to differences among islands in mean coral-colony densities. In addition, the frequency and severity of natural and anthropogenic disturbances, including crown-of-thorns seastar (COTS) outbreaks, typhoons, fishing, water-quality degradation, and runoff, may influence the dynamics of coral community structure at these islands (Burdick et al. 2008; Richmond et al. 2008; Starmer et al. 2008; Houk and Starmer 2010). Among the 8 northern islands surveyed in 2007, overall mean colony density was the lowest at Farallon de Pajaros with 33.7 colonies m^{-2} (SE 3.4; Fig. 3.4.1d). At Farallon de Pajaros, the patchy distribution of hard substrate meant that considerable portions of most survey transects covered habitats characterized by unoccupied basalt boulders intermingled with noncarbonate sand. Farallon de Pajaros is an active volcano that has erupted at least 15 times since the mid-19th century (see Chapter 17: "Farallon de Pajaros," Section 17.1: "Introduction"). Marine substrate instability, in combination with recurrent landslides and ash fall, may limit coral recruitment and development in the shallow, well-lit habitats around this island.
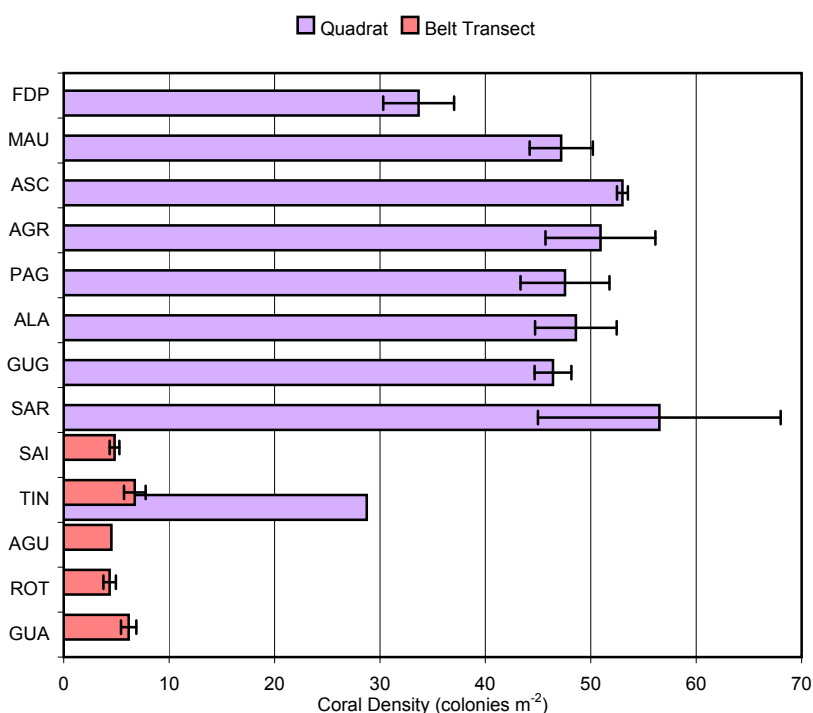
Figure 3.4.1d. Mean overall coral-colony densities of hard corals from REA benthic surveys of forereef habitats conducted in the Mariana Archipelago during MARAMP 2007. The quadrat method was used in surveys at the northern islands, and the belt-transect method was used in surveys at 5 southern islands, with the exception of Tinian, where both methods were used. Error bars indicate standard error (± 1 SE) of the mean.

The previously mentioned differences in the methods implemented to census corals during MARAMP 2007 bias survey results relating to size distribution, and, therefore, we only compare size distribution within regions surveyed with the same method (At Tinian in 2007, 4 REA sites were surveyed using the belt-transect method and 1 site was surveyed using the quadrat method. For comparison of estimates among the southern islands, this discussion of size-class distribution excludes data from the single site at Tinian where quadrat surveys were completed.) Among the 5 southern islands surveyed in 2007 using the belt-transect method, size-class distribution did not vary substantially (Fig. 3.4.1e). Of the colonies surveyed at Guam, Rota, Aguijan, Tinian, and Saipan, 68%–81% had maximum diameters ≤ 10 cm, and < 3% had maximum diameters > 40 cm. No colonies with maximum diameters > 160 cm were recorded. At the 8 northern islands surveyed in 2007, where the quadrat method was used, 63%–93% of all colonies exhibited a maximum diameter ≤ 5 cm, with Farallon

de Pajaros having the largest proportion (93%) of small colonies (maximum diameter of 0–5 cm; Fig. 3.4.1e). In addition, at the northern islands, a very small proportion of colonies (< 2%) had maximum diameters > 40 cm, and no colonies with maximum diameters > 160 cm were found.

Figure 3.4.1.e. Size-class distribution of hard corals by island from REA benthic surveys of forereef habitats conducted in the Mariana Archipelago during MARAMP 2007. The quadrat method was used in surveys at the northern islands, and the belt-transect method was used in surveys at 5 southern islands, with the exception of Tinian, where both methods were used.
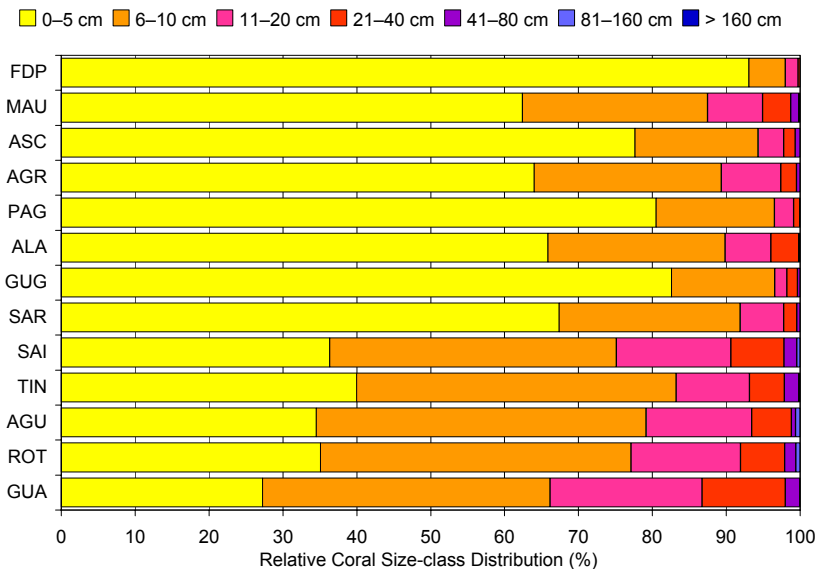
3.4.2 Surveys for Coral Disease and Predation

Based on REA benthic surveys of hard corals on forereef habitats, overall mean prevalence of coral disease was highest in the southern islands with the greatest value of 1.4% (SE 0.4) recorded at Guam, where hot spots on the northern and north-western coasts had the highest number of cases and overall prevalence of 2.7%–3.9%. The next-greatest levels of disease were seen at Saipan with 0.4% (SE 0.2), Tinian with 0.2% (SE 0.1), and Rota with 0.06% (SE 0.03), and overall mean prevalence of coral disease was lowest in the northern islands with mean values ≤ 0.04% (Fig. 3.4.2a; the values of overall prevalence shown in this figure include predation). The southern islands accounted for 74% of cases of bleaching and disease observed in the Mariana Archipelago. Guam and Saipan not only are the largest islands in the Mariana Archipelago but also possess the greatest estimated potential reef areas, likely harboring the most extensive coral reef development in the Mariana Archipelago. Guam and Saipan also have the largest human populations in this region, and the associated deterioration in water quality and habitat might be linked to the greater levels of disease seen at these islands compared to observations at other islands in this archipelago. Elevated water temperatures and disturbances from human activities have been noted as environmental drivers of disease; thus, the coral reef ecosystems at the populated, southern islands may have a greater risk of coral bleaching and marine disease outbreaks than do the reefs at the mostly uninhabited northern islands

Figure 3.4.2a. Mean overall prevalence (%) of coral diseases and predation from REA benthic surveys of forereef habitats conducted in the Mariana Archipelago during MARAMP 2007. Prevalence was computed based on the estimated total number of coral colonies within the area surveyed for disease at each REA site. The quadrat method was used in surveys at the northern islands, and the belt-transect method was used in surveys at 5 southern islands, with the exception of Tinian, where both methods were used. Error bars indicate standard error (± 1 SE) of the mean.
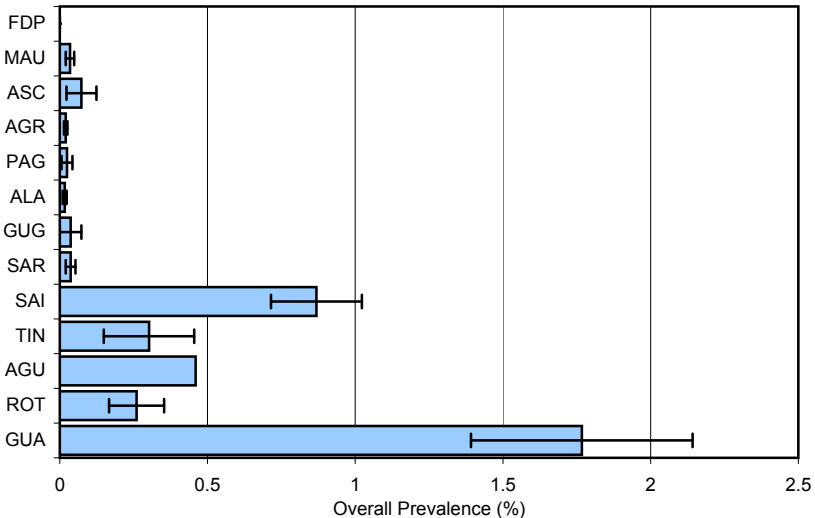
(Kaczmarsky 2006; Harvell et al. 2007; Vargas-Ángel and Wheeler 2009). However, because 2 different methods were implemented to census corals, as discussed previously in this section, survey results reflect biases toward lower colony densities and, thus, larger values of disease prevalence for the southern islands and higher colony densities and, thus, smaller values of disease prevalence for the northern islands, making quantitative, interisland comparisons inappropriate.

Bleaching and at least 6 broad disease types (Vargas-Ángel and Wheeler 2009; PIFSC 2009) were identified in 2007 in the Mariana Archipelago. Similar types of disease conditions have been reported for reefs in other Pacific regions, including American Samoa, the Great Barrier Reef, the Philippines, east Africa, and the Red Sea (Raymundo et al. 2008; Brainard et al. 2008; Kaczmarsky 2006; Work and Rameyer 2005; Loya 2004; Willis et al. 2004; Winkler et al. 2004). During MARAMP 2007, fungal infection, bleaching, and pigmentation response ranked as the 3 most common disease conditions archipelago-wide, representing ~ 30%, 23%, and 19% of cases. Although bleaching, pigmentation response, and fungal infections can occur naturally, elevated prevalence and disease hotspots may be indicative of balance shifts between host, agent, and the environment. In addition, recently, University of Guam and CRED scientists have identified the occurrence of additional diseases in this archipelago, including black-band disease, brown-band disease, skeletal eroding band disease, and ulcerative white spot disease, a type of subacute tissue loss (Burdick et al. 2008; LJ Raymundo pers. comm.; B Vargas-Ángel, unpublished data).

Table 3.4.2a Archipelago-wide disease occurrence, measured as percentage of cases, among coral families and genera from REA benthic surveys of forereef habitats conducted in the Mariana Archipelago during MARAMP 2007. BLE: bleaching; WSY: white syndrome; TLS: subacute tissue loss; SGA: skeletal growth anomalies; PRS: pigmentation response; FUN: fungal infection; OTH: algal and cyanophyte infections and other lesions of unknown etiology; PRE: predation by COTS or corallivorous snails.

Family	Genus	BLE	WSY	TLS	SGA	PRS	FUN	OTH	Total	PRE
Acroporidae	*Acropora*	–	–	–	0.9	–	–	–	0.9	5.3
	Astreopora	10.6	–	–	0.9	–	0.4	0.4	12.3	12.4
	Montipora	2.1	–	0.9	0.4	–	0.4	0.4	4.3	4.7
Pocilloporidae	*Pocillopora*	–	–	–	–	–	–	0.4	0.4	10.1
	Stylophora	–	–	–	–	–	–	–	–	10.1
Oculinidae	*Galaxea*	–	–	–	–	–	–	0.4	0.4	0.6
Siderastreidae	*Coscinaraea*	–	–	–	–	–	0.4	–	0.4	–
	Psammocora	0.4	–	–	–	–	0.9	–	1.3	–
Agariciidae	*Pavona*	–	–	–	–	–	0.4	1.3	1.7	1.2
	Gardineroseris	–	0.9	–	–	–	–	0.4	1.3	–
Fungidae	*Fungia*	–	–	–	–	–	–	–	–	1.8
Merulinidae	*Hydnophora*	–	–	–	–	–	0.4	–	0.4	–
Dendrophyliidae	*Turbinaria*	–	–	–	–	–	–	0.4	0.4	–
Mussidae	*Lobophyllia*	–	–	–	0.4	–	–	–	0.4	–
Faviidae	*Favia*	0.4	–	–	–	–	0.9	0.4	1.7	4.1
	Favites	–	–	–	–	–	–	–	–	0.6
	Goniastrea	0.9	0.4	–	–	–	–	0.4	1.7	26.6
	Platygyra	3.0	–	–	–	–	–	–	3.0	–
	Leptoria	–	–	–	–	–	–	–	–	0.6
	Plesiastrea	0.4	–	–	–	–	–	–	0.4	–
	Cyphastrea	–	–	–	–	–	19.1	–	19.1	1.2
	Echinopora	0.9	–	–	–	–	–	–	0.9	–
Poritidae	*Porites*	4.7	0.9	7.7	3.0	18.7	6.8	6.0	47.7	20.7
	Goniopora	–	–	0.9	–	–	–	0.4	1.3	–
Total		23.4	2.1	9.4	5.5	18.7	29.8	11.1	100.0	100.0

The diseases enumerated across the Mariana Archipelago affected 24 hard coral genera belonging to 11 families (Table 3.4.2a). The families Poritidae, Faviidae, and Acroporidae accounted for more than 93% of all cases, with *Porites*, *Cyphastrea*, and *Astreopora* each hosting 1 major disease state: pigmentation response, fungal infection, and bleaching, respectively. Collectively, these 3 genera hosted nearly 80% of all disease cases archipelago-wide. Patterns of disease occurrence (percentage of cases) from MARAMP 2007 suggest that the family Poritidae hosted all 7 major disease categories, while Acroporidae and Faviidae hosted 5 and 4 disease states (Table 3.4.2a). The disproportionate susceptibility to disease in the Indo-Pacific of the Poritidae, Faviidae, and Acroporidae has been broadly documented (Willis et al. 2004; Vargas-Ángel 2009; Aeby 2006).

Predation scars inflicted by COTS or corallivorous snails, such as snails from the genus *Drupella*, were common, with 4 islands containing 82% of all cases enumerated during MARAMP 2007. These islands were Saipan, Guam, Maug, and Asuncion. The remaining cases were recorded at Rota, Tinian, Pagan, and Agrihan but at much lower levels. No signs of COTS or snail predation were noted at Farallon de Pajaros, Aguijan, Alamagan, Guguan, or Sarigan. Signs of COTS and snail predation were observed on 14 genera, belonging to 7 families of hard corals, with members of the Faviidae, Acroporidae, Poritidae, and Pocilloporidae presenting more than 96% of all scars (Table 3.4.2.a). In these families, 3 genera alone, *Goniastrea*, *Porites*, and *Astreopora*, presented 60% of all cases. Interestingly, 50% of all scars observed at the northern islands of Asuncion and Maug were seen on colonies of *Goniastrea*, whereas, at the populated, southern islands of Guam and Saipan, *Astreopora*, *Porites*, *Pocillopora*, and *Stylophora* presentend more than 60% of cases (Fig. 3.4.2b). Prey distribution and abundance, as well as predator selectivity, can strongly affect the patterns and intensity of COTS and snail predation on hard-coral benthos.

These results from MARAMP 2007 represent the first comprehensive attempt to quantitatively assess the distribution and prevalence of coral diseases in Guam and the CNMI. Although archipelago-wide means of overall prevalence are relatively low, site-specific hotspots occurred at Guam. In addition, the coral families Poritidae, Acroporidae, and Faviidae appeared to be disproportionately susceptible to disease and predation. Potential outbreaks of host-specific diseases or corallivores can be a source of concern, given that these families are key contributors to reef building and ecosystem structural dynamics across the Mariana Archipelago.

Figure 3.4.2b. Overall mean prevalence (%) observations of hard-coral genera affected by coral diseases and predation from REA benthic surveys of forereef habitats conducted in the Mariana Archipelago during MARAMP 2007. The order of taxa presented in the bars is the same as the order in the legend. The quadrat method was used in surveys at the northern islands, and the belt-transect method was used in surveys at 5 southern islands, with the exception of Tinian, where both methods were used.
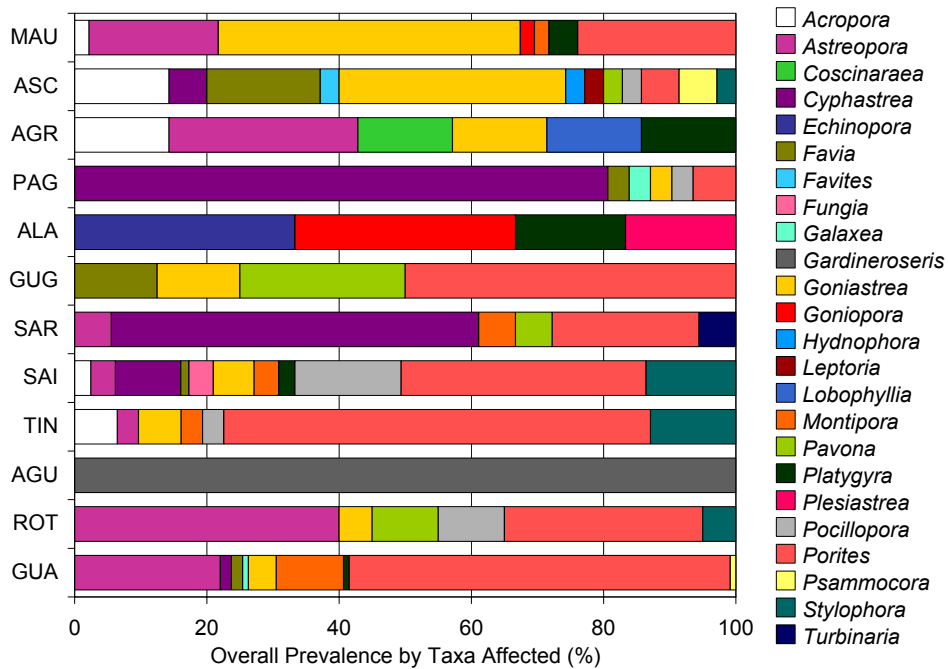
3.5   Algae and Algal Disease

3.5.1   Algal Surveys

Algal Cover: Macroalgae and Turf Algae

The most apparent spatial pattern in mean macroalgal cover, based on towed-diver surveys conducted during MARAMP 2005 and 2007, was that observed values were higher at the populated, southern islands than at the northern islands of the Mariana Archipelago (Fig. 3.5.1a). For both of these survey years, among the islands of this archipelago, Guam, Tinian, and Rota registered the highest mean macroalgal cover with overall means ranging from 39% (SE 2) to 56% (SE 1.5). The lowest levels in the Mariana Archipelago were recorded at Farallon de Pajaros and Ascuncion in 2005, with islandwide means of 4% (SE 1.3) and 5% (SE 1.3), and at Farallon de Pajaros in 2007, with an overall mean of 3% (SE 0.4). When considering the offshore and remote reefs and banks, a similar spatial pattern was noted during towed-diver surveys in 2005, with Santa Rosa Reef, located south of Guam, having the highest macroalgal cover in the Mariana Archipelago with an overall mean of 71% (SE 3.1). At Arakane and Pathfinder Reefs on the West Mariana Ridge, mean macroalgal cover was 46% (SE 2.3) and 29% (SE 1.1) in 2005.

A similar spatial pattern in macroalgal cover was observed during REA benthic surveys using the line-point-intercept method during MARAMP 2007: relatively high overall means of macroalgal cover were recorded at the populated, southern islands, and the lowest level of macroalgal cover was observed at northern islands (Fig. 3.5.1a). No macroalgae were recorded at Farallon de Pajaros and Agrihan.

Results from towed-diver surveys conducted during MARAMP 2003 suggest relatively consistent and high values of algal cover in 2003 throughout the Mariana Archipelago (Fig. 3.5.1a) with overall means for macroalgae and turf algae combined ranging from 35% to 68%, excluding the ash-covered reefs of Anatahan, which had much lower algal cover. During MARAMP 2003, the protocol for towed-diver benthic surveys aggregated observations of both turf algae and macroalgae into a single category. In contrast, MARAMP 2005 and 2007 towed-diver surveys recorded macroalgal cover as a distinct category and did not record cover of turf algae within field estimations. Thus, temporal comparisons of estimates for the "macroalgae" category between MARAMP 2003 and the later survey periods are not appropriate.

A general decline in macroalgal cover was observed between MARAMP 2005 and 2007 (Fig. 3.5.1a). Decreases in overall macroalgal cover were noted at 8 of the 13 islands surveyed, with reductions in overall means ranging from 7% at Rota to 19% at Maug. At Guguan, estimates of microalgal cover were 10% higher in 2007 than in 2005. At Asuncion, estimates increased by 14%. Observed overall macroalgal cover essentially remained the same at Saipan, Pagan, and Farallon de Pajaros between 2005 and 2007. No other distinct temporal patterns for macroalgal cover were identified across the Mariana Archipelago between MARAMP 2005 and 2007.

Algal Cover: Crustose Coralline Red Algae

Observations of crustose coralline red algae from towed-diver surveys suggest low cover levels throughout the Mariana Archipelago, compared to values recorded at other areas in the Pacific surveyed through the Pacific RAMP. Around a majority of islands, offshore banks and remote reefs, overall mean cover of crustose coralline red algae was ≤ 16% during MARAMP 2003, 2005, and 2007 (Fig. 3.5.1b). An exception was noted for Supply Reef, where the overall observed mean cover of crustose coralline red algae was 35% (SE 5.8) during MARAMP 2003. Low levels of crustose-coralline-red-algal cover also were seen during REA surveys conducted using the line-point-intercept method in 2007, with overall sample means ≤ 13%, except for at Aguijan, where an estimate of 32.4% was recorded at the only site surveyed there in 2007.

No difference in cover of crustose coralline red algae was observed between the northern and southern islands, based on results from both towed-diver and REA benthic surveys. No temporal patterns in cover values from towed-diver surveys for crustose coralline red algae were detected across the Mariana Archipelago between the 3 MARAMP surveys (Fig. 3.5.1b).

Figure 3.5.1a. Spatial and temporal comparison of mean macroalgal cover (%) from REA and towed-diver benthic surveys of forereef habitats conducted in the Mariana Archipelago during MARAMP 2003, 2005, and 2007. The 2003 panel shows towed-diver observations of both macroalgae and turf (towed-diver surveys included turf algae only during MARAMP 2003). Error bars indicate standard error (± 1 SE) of the mean.
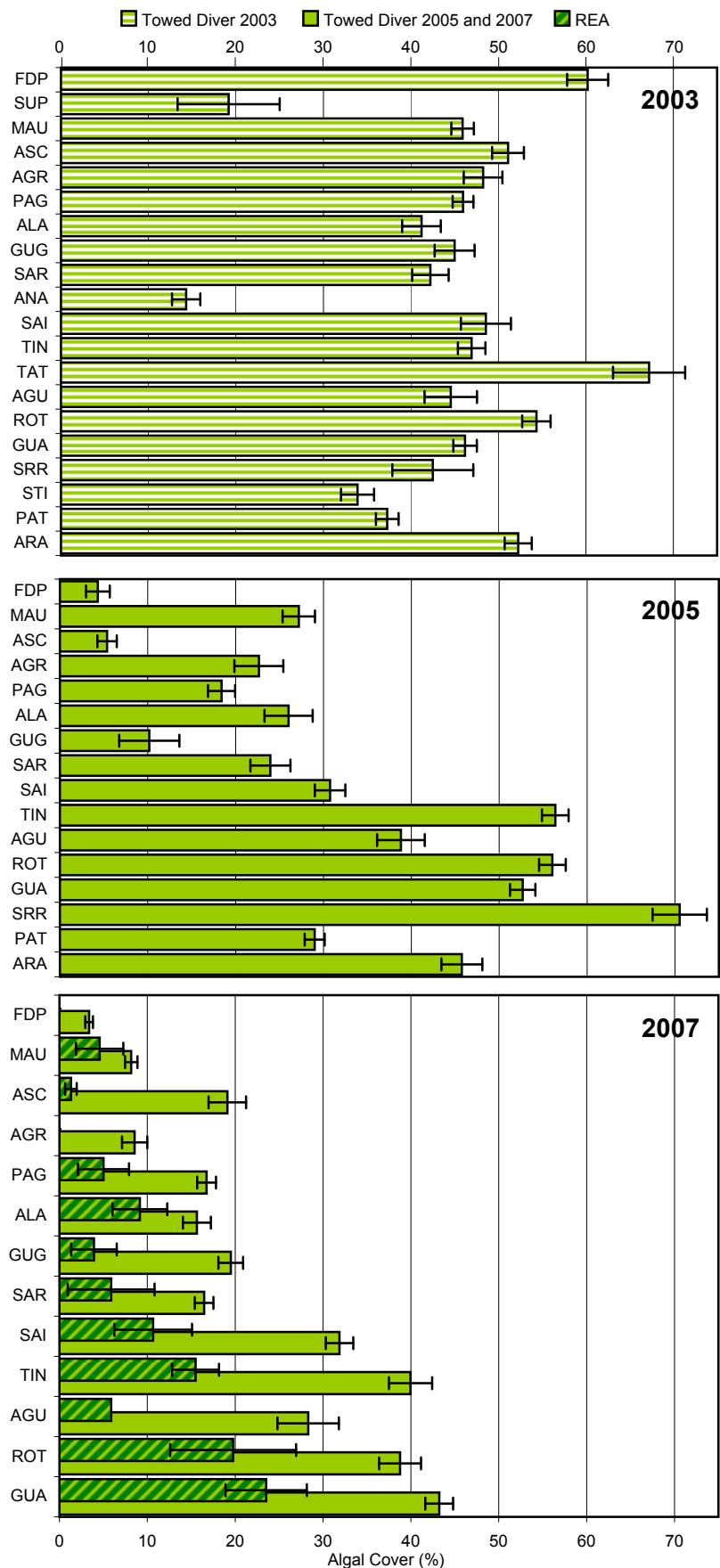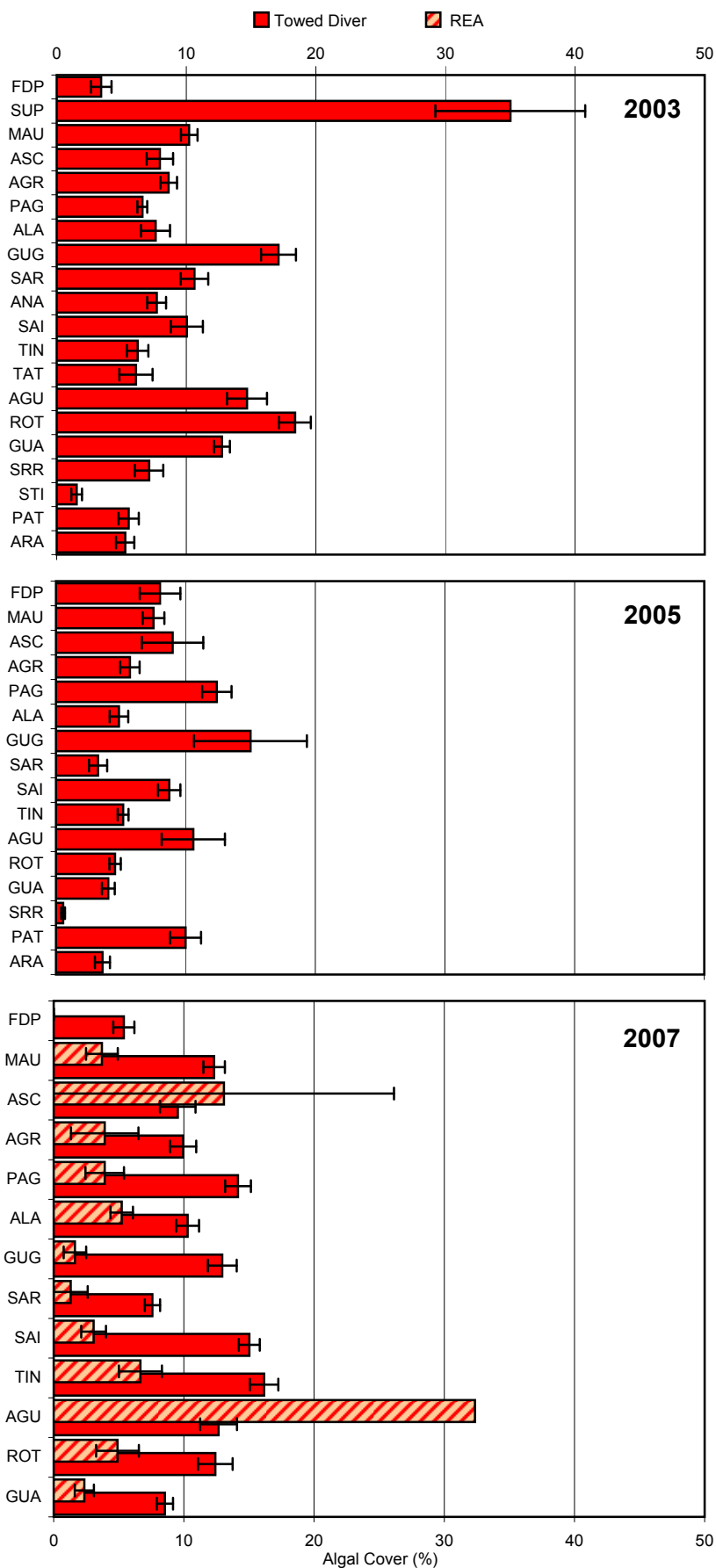
Figure 3.5.1b. Spatial and temporal comparison of mean crustose-coralline-red-algal cover (%) from REA and towed-diver benthic surveys of forereef habitats conducted in the Mariana Archipelago during MARAMP 2003, 2005, and 2007. Error bars indicate standard error (± 1 SE) of the mean.

Occurrence and Abundance: Macroalgal Genera and Functional Groups

Tribollet and Vroom (2007) used CRED data from REA benthic surveys to examine spatial and temporal trends of macroalgal distribution and abundance in the Mariana Archipelago between 2003 and 2005. They found considerable differences in algal communities between the volcanic, northern islands and carbonate, southern islands and hypothesized that, in this archipelago, larger islands likely harbor greater algal diversity than do smaller islands. In support of this premise, data from REA benthic surveys conducted during the 3 MARAMP survey years, suggest that total generic richness for macroalgae was tied to island and reef size, as the larger, southern islands contained the largest reef areas (at depths < 30 m) and supported more macroalgal genera than did the smaller, northern islands (Table 3.5.1a and Fig. 3.5.1c).

This difference in generic richness was expected, since larger islands typically contain a more diverse array of habitats and, consequently, more niches that can support more biologically diverse populations. Still, it was of concern that the higher number of species encountered at larger islands may have been the result of skewed sampling efforts (e.g., larger islands received a greater survey effort than smaller islands during MARAMP surveys) until the overall means for each island were compared. When the average number of macroalgal genera found at each REA site per island was plotted against island and reef size, sites at larger islands still appeared to contain greater diversity than sites at smaller islands, suggesting that larger islands likely support more diverse algal communities than do smaller islands (Fig. 3.5.1c).

The greatest diversity of macroalgae was observed at Guam, where 54 macroalgal genera were recorded across the 3 MARAMP survey years (Fig. 3.5.1c and Table 3.5.1a). Looking at average generic richness for macroalgae, the highest values were recorded at Rota, Guam, and Tinian with overall means of 13.1(SE 0.74), 13 (SE 0.68), and 12.7 (SE 1.25) genera per site. Among the islands surveyed, excluding Anatahan, where surveys were conducted only in 2003, Farallon de Pajaros had the lowest macroalgal diversity with 13 total genera observed and an overall mean of 6 (SE 0.47) genera per site. Among the northern islands, Pagan had the highest macroalgal diversity with 40 total genera enumerated and an overall mean richness of 11.1 (SE 0.61) genera per site. Note that the generic richness numbers presented in this chapter include data data from roving-diver surveys in addition to photoquadrat surveys. The counts of taxa provided in the island chapters, however, include only data from photoquadrats (see Chapter 2: "Methods and Operational Background," Section 2.4.6: "Algae and Algal Disease").
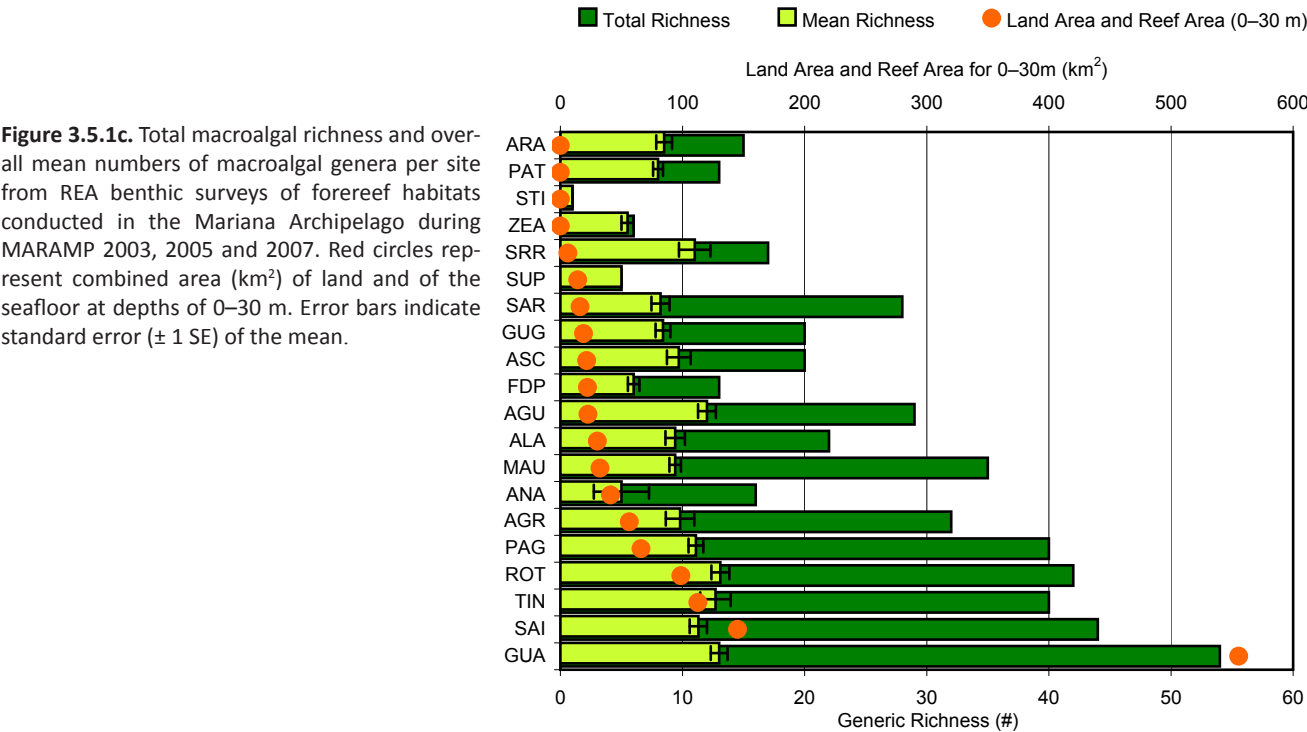
Figure 3.5.1c. Total macroalgal richness and overall mean numbers of macroalgal genera per site from REA benthic surveys of forereef habitats conducted in the Mariana Archipelago during MARAMP 2003, 2005 and 2007. Red circles represent combined area (km²) of land and of the seafloor at depths of 0–30 m. Error bars indicate standard error (± 1 SE) of the mean.

Island	Survey Year	Number of Genera or Functional Group				
		Green Macroalgae	Red Macroalgae	Brown Macroalgae	Macroalgal Total	Algal Functional Group
FDP	2003	7	0	3	10	2
	2005	6	1	3	10	1
	2007	4	3	2	9	3
	Total	7	3	3	13	3
SUP	2003	3	1	1	5	3
MAU	2003	10	9	4	23	3
	2005	10	7	3	20	4
	2007	8	8	6	22	3
	Total	14	15	6	35	4
ASC	2003	8	7	3	18	3
	2005	7	2	3	12	3
	2007	7	5	3	15	3
	Total	9	8	3	20	3
AGR	2003	10	9	4	23	3
	2005	8	4	3	15	4
	2007	6	10	4	20	3
	Total	11	15	6	32	4
PAG	2003	11	12	4	27	3
	2005	11	13	3	27	4
	2007	10	17	4	31	3
	Total	13	22	5	40	4
ALA	2003	5	8	1	14	3
	2005	5	8	2	15	3
	2007	5	6	2	13	3
	Total	8	11	3	22	3
GUG	2003	8	5	1	14	3
	2005	3	1	1	5	2
	2007	7	6	2	15	3
	Total	10	8	2	20	3
ZEA	2003	5	1	0	6	1
SAR	2003	8	2	0	10	2
	2005	8	10	2	20	2
	2007	5	4	2	11	3
	Total	12	13	3	28	3
ANA	2003	7	7	2	16	3
SAI	2003	9	9	2	20	3
	2005	12	13	4	29	4
	2007	13	17	2	32	3
	Total	16	24	4	44	2
TIN	2003	6	8	2	16	3
	2005	15	14	4	33	4
	2007	8	13	2	23	3
	Total	15	21	4	40	4
AGU	2003	9	7	0	16	3
	2005	11	7	4	22	4
	2007	7	5	0	12	3
	Total	13	12	4	29	4
ROT	2003	14	15	3	32	4
	2005	15	12	4	31	3
	2007	11	10	3	24	3
	Total	16	22	4	42	4
GUA	2003	14	15	3	32	4
	2005	15	22	3	40	4
	2007	13	19	5	37	3
	Total	19	30	5	54	4
SRR	2003	8	3	0	11	4
	2005	11	3	1	15	4
	Total	12	4	1	17	4
STI	2003	0	1	0	1	1
PAT	2003	6	3	0	9	3
	2005	7	3	1	11	3
	Total	7	5	1	13	3
ARA	2003	9	1	0	10	3
	2005	9	3	1	13	3
	Total	11	3	1	15	3

Table 3.5.1a. Total number of macroalgal genera and algal functional groups observed at each island or reef from REA benthic surveys of forereef habitats conducted in the Mariana Archipelago during MARAMP 2003, 2005 and 2007. The last column counts the total number of groups in addition to macroalgae: turf algae, crustose coralline red algae, branched non-geniculate coralline red algae, and cyanophytes. See Appendices B and C for lists of genera found at each island or reef.

Distribution of individual macroalgal genera across the Mariana Archipelago during the 3 MARAMP survey years is presented in Appendices B and C. Among green algae, the genera *Caulerpa*, *Dictyosphaeria*, *Halimeda*, *Neomeris*, and *Ventricaria* were ubiquitous across all islands and banks in the Mariana Archipelago. Such broad distributions were not as common among genera of red and brown algae, with only the red algal genus *Dichotomaria* and brown algal genus *Dictyota* commonly occurring throughout both the islands and banks of this archipelago. Other algae, such as the red genera *Actinotrichia*, *Jania*, and *Peyssonnelia*, the brown genera *Padina* and *Turbinaria*, and the green genus *Tydemania* were encountered primarily in reef habitats surrounding emergent islands and rarely on submerged banks.

Figure 3.5.1d. Spatial and temporal comparison of relative occurrence (%) for select macroalgal genera and algal functional groups from REA benthic surveys of forereef habitats conducted in the Mariana Archipelago during MARAMP 2003, 2005, and 2007.
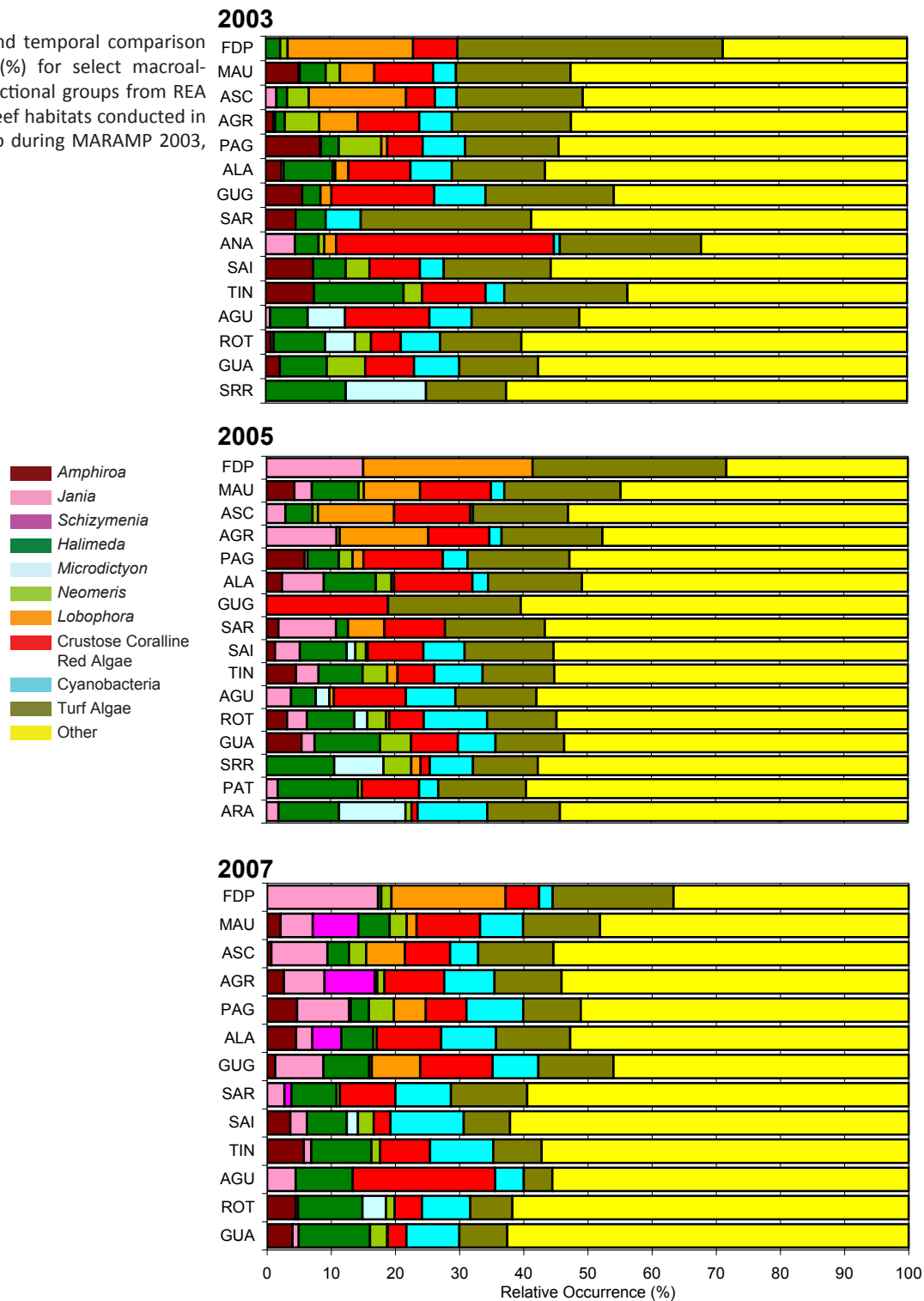
Differences in macroalgal biodiversity between the volcanically active, northern islands and carbonate, southern islands were also obvious, especially among red algae (Appendices B and C). The red algal genera *Amansia*, *Crouania*, *Gelidiella*, *Haloplegma*, *Halymenia*, and *Predaea* were common at southern islands, but they were rare or absent during surveys conducted at islands north of Saipan. An opposite distribution was observed for the red algal genera *Cheilosporum* and *Dasya*, which commonly occurred at northern islands rather than at southern islands.

Island	Survey Year	Green Macroalgal Genera			Red Macroalgal Genera			Brown Macroalgal Genera	Algal Functional Group		
		Halimeda	*Microdictyon*	*Neomeris*	*Amphiroa*	*Jania*	*Schizymenia*	*Lobophora*	Crustose Coralline Red Algae	Cyanobacteria	Turf Algae
FDP	2003	4.2	0.0	2.1	0.0	0.0	0.0	35.4	12.5	0.0	75.0
	2005	0.0	0.0	0.0	0.0	44.4	0.0	77.8	0.0	0.0	88.9
	2007	2.8	0.0	8.3	0.0	91.7	0.0	94.4	27.8	11.1	100.0
MAU	2003	18.8	0.0	10.4	24.0	1.0	0.0	25.0	42.7	16.7	83.3
	2005	32.4	0.0	3.7	19.4	12.0	0.0	38.9	49.1	9.3	80.6
	2007	32.4	0.0	17.6	13.9	33.3	47.2	10.2	65.7	44.4	79.6
ASC	2003	8.3	0.0	16.7	0.0	8.3	0.0	75.0	22.2	16.7	97.2
	2005	27.8	0.0	5.6	0.0	19.4	0.0	77.8	77.8	2.8	97.2
	2007	27.8	0.0	22.2	5.6	72.2	0.0	50.0	58.3	36.1	97.2
AGR	2003	6.9	0.0	25.0	5.6	1.4	0.0	27.8	44.4	23.6	86.1
	2005	0.0	0.0	2.8	0.0	63.9	0.0	80.6	55.6	11.1	91.7
	2007	2.8	0.0	8.3	19.4	47.2	58.3	0.0	69.4	58.3	77.8
PAG	2003	15.6	0.0	37.5	47.9	1.0	0.0	5.2	31.3	37.5	82.3
	2005	29.6	0.0	13.0	36.1	2.8	0.0	10.2	75.0	23.1	96.3
	2007	26.9	0.0	37.0	44.4	76.9	2.8	47.2	60.2	84.3	85.2
ALA	2003	52.8	0.0	2.8	16.7	2.8	0.0	13.9	66.7	44.4	100.0
	2005	55.6	0.0	16.7	16.7	44.4	0.0	2.8	83.3	16.7	100.0
	2007	41.7	0.0	4.2	37.5	20.8	37.5	0.0	83.3	70.8	95.8
GUG	2003	13.9	0.0	0.0	27.8	0.0	0.0	8.3	77.8	38.9	97.2
	2005	0.0	0.0	0.0	0.0	0.0	0.0	0.0	91.7	0.0	100.0
	2007	56.7	0.0	3.3	10.0	60.0	0.0	60.0	90.0	56.7	93.3
SAR	2003	16.7	0.0	0.0	16.7	0.0	0.0	0.0	0.0	19.4	94.4
	2005	11.1	0.0	0.0	11.1	52.8	0.0	33.3	55.6	0.0	91.7
	2007	36.1	0.0	2.8	0.0	13.9	5.6	0.0	44.4	44.4	61.1
ANA	2003	8.3	0.0	2.1	0.0	10.4	0.0	4.2	77.1	2.1	50.0
SAI	2003	30.6	0.0	22.2	44.4	0.0	0.0	0.0	47.2	22.2	100.0
	2005	51.0	9.4	11.5	9.4	27.1	0.0	2.1	60.4	44.8	96.9
	2007	44.8	12.5	17.7	26.0	18.8	0.0	0.0	18.8	82.3	52.1
TIN	2003	66.7	0.0	13.9	36.1	0.0	0.0	0.0	47.2	13.9	91.7
	2005	59.7	0.0	33.3	40.3	30.6	0.0	13.9	50.0	65.3	97.2
	2007	68.3	0.0	10.0	41.7	8.3	0.0	0.0	56.7	71.7	55.0
AGU	2003	33.3	33.3	0.0	0.0	4.2	0.0	0.0	75.0	37.5	95.8
	2005	30.6	16.7	0.0	0.0	30.6	0.0	5.6	88.9	61.1	100.0
	2007	33.3	0.0	0.0	0.0	16.7	0.0	0.0	83.3	16.7	16.7
ROT	2003	63.3	36.7	20.0	6.7	3.3	0.0	0.0	36.7	48.3	100.0
	2005	66.7	18.1	26.4	29.2	27.8	0.0	4.2	48.6	88.9	97.2
	2007	72.2	26.4	9.7	31.9	2.8	0.0	0.0	30.6	54.2	47.2
GUA	2003	58.3	0.0	47.9	17.7	0.0	0.0	0.0	60.4	56.3	97.9
	2005	95.2	0.0	45.2	51.2	19.0	0.0	0.0	67.9	54.8	100.0
	2007	86.7	0.0	20.8	30.8	7.5	0.0	0.8	22.5	64.2	58.3
SRR	2003	100.0	100.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	100.0
	2005	91.7	66.7	37.5	0.0	0.0	0.0	12.5	12.5	58.3	87.5
PAT	2005	87.5	0.0	4.2	0.0	12.5	0.0	0.0	62.5	20.8	95.8
ARA	2005	83.3	91.7	8.3	0.0	16.7	0.0	0.0	8.3	95.8	100.0

Table 3.5.1b. Observations of occurrence (%) for select macroalgal genera and algal functional groups at each island or reef from REA benthic surveys of forereef habitats conducted in the Mariana Archipelago during MARAMP 2003, 2005, and 2007.

Algal diversity is expected to change seasonally, which can confound comparisons of results among MARAMP survey periods that occurred during different times of year (MARAMP 2003 and 2005 occurred during the fall, but MARAMP 2007 occurred during the spring). For example, the red algal genus *Schizymenia* was only recorded in 2007 and not in 2003 or 2005 (Appendix B). Whether this difference was caused by seasonal preferences for the macroscopic phase of this alga or an actual permanent increase in population density cannot be determined from the data collected. The majority of algal genera encountered did not appear to show seasonal preferences, and estimates of their occurrence remained relatively static throughout the 3 MARAMP survey years presented in this report.

Occurrence, measured as the percentage of photoquadrats in which an algal genus was recorded, was compared among islands and years for select algal genera and functional groups to provide an idea of whether composition of common algal components differed spatially or temporally across the Mariana Archipelago (Fig. 3.5.1d and Table 3.5.1b). Some genera, such as the calcified, sediment-producing, green alga *Halimeda*, were commonly found at all islands across this archipelago (see also Tribollet and Vroom 2007), although younger reef systems, such as the reefs found at Farallon de Pajaros, had a lower abundance of this genus than older reefs located toward the southern end of the Mariana Arc. Other genera, such as the green alga *Microdictyon*, were not recorded in photoquadrats at northern islands but occurred in relatively dense populations on southern islands and banks. In contrast, the brown algal genus *Lobophora* was common on reefs surrounding volcanic, northern islands but was uncommon on reefs at carbonate, southern islands (Table 3.5.1b).

Temporally, observations for some macroalgal genera, such as *Halimeda* and the red alga *Amphiroa*, did not show changes in occurrence from 2003 to 2007 (Table 3.5.1b). For other taxa, such as the red algal genera *Jania* and *Schizymenia*, changes in population density over time were observed. The genus *Jania* was relatively scarce in 2003 and became very abundant in 2005 and then slightly less common by 2007. The genus *Schizymenia* was not recorded at all until MARAMP 2007, when it became extremely abundant at 3 islands on the northern end of the Mariana Arc: Maug, Agrihan, and Alamagan (Table 3.5.1b).

Crustose coralline red algae and turf algae were ubiquitous across the Mariana Archipelago in each of the 3 MARAMP survey periods (Table 3.5.1b). This finding is not surprising, since both of these functional groups are known to play dominant roles in healthy reef ecosystems globally. Crustose coralline red algae are critical for cementing together loose rubble and consolidating reefs, and they serve as necessary settling surfaces for many invertebrate larvae. Turf algae are essential food sources for many marine herbivores. Cyanobacteria were typically less prevalent than other algal functional groups at northern islands; however, their abundance was greater at populated, southern islands during each of the 3 MARAMP survey years with percentages of occurrence comparable to the levels seen for turf algae and crustose coralline red algae (Table 3.5.1b)

3.5.2   Surveys for Coralline-algal Disease

During MARAMP 2007, coralline-algal diseases were recorded at 9 of the 13 islands surveyed, with no disease found at Sarigan, Alamagan, Agrihan, and Farallon de Pajaros (Fig. 3.5.2a). Correspondingly, disease conditions were observed at 25 (~ 38%) of the 66 REA sites surveyed, with Tinian alone containing more than 26% of all cases enumerated in 2007. The northern islands as a group accounted for only 13% of cases documented. Records for all sites combined yielded an archipelago-wide mean density of 0.9 cases 100 m^{-2} (SE 0.3), with values ranging from a minimum of 0.3 cases 100 m^{-2} at several sites at the populated, southern islands of Tinian, Saipan, and Rota to a maximum of 15.4 cases 100 m^{-2} at a north-facing site off the coast of Aguijan. Excluding Aguijan, where only one site was surveyed, the highest overall observed mean density of coralline-algal disease was found at Tinian with 2.8 cases 100 m^{-2} (SE 1.5), followed by Guam with 1.6 cases 100 m^{-2} (SE 0.8), Rota with 0.8 cases 100 m^{-2} (SE 0.4), Saipan with 0.7 cases 100 m^{-2} (SE 0.3), and Maug with 0.4 cases 100 m^{-2} (SE 0.3). Overall means were < 0.1 cases 100 m^{-2} for each of the other 3 islands that contained coralline-algal disease.

Three broad disease categories were recorded during MARAMP 2007: coralline lethal orange disease, coralline white band syndrome, and coralline cyanobacterial disease. Although prior field surveys (Starmer et al. 2008; T.J. Goreau, Global Coral Reef Alliance, pers. comm.) have identified the presence of coralline-algal disease in this region, the results from MARAMP 2007 represent the first attempt to quantitatively evaluate the occurrence of these diseases in the Mariana Archipelago. In this context, patterns of disease distribution and abundance indicate that some disease states were common and widespread and others were uncommon and rare. Of the 124 coralline-algal disease cases enumerated in 2007, more than 87% were cases of coralline lethal orange disease, followed by coralline white band syndrome (12%), and coralline cyanobacterial disease (~ 1%). Coralline lethal orange disease was not only the most widespread coralline-algal disease

but also the only disease condition identified at 4 of the 9 islands containing disease: Guam, Rota, Aguijan, and Maug. Conditions of coralline white band syndrome were enumerated at both Saipan and Tinian, with Tinian containing 93% of all cases of this syndrome. Lastly, only one case of coralline cyanobacterial disease, at Saipan between Puntans Halaihai and Laolao Kattan in the east region, was detected during disease surveys in this archipelago.

Although archipelago-wide mean density of coralline-algal diseases was low with 0.9 cases 100 m^{-2} (SE 0.3), elevated site-specific densities occurred at Aguijan with 15.4 cases 100 m^{-2}, Tinian with 8.3 cases 100 m^{-2}, and Guam with 8 cases 100 m^{-2}. These findings suggest that these areas offer biological and environmental conditions that may favor the proliferation of coralline-algal disease. Rapidly declining populations of coralline algae in many tropical reefs are the result of not only reduced water quality and sedimentation (Fabricius and De'ath 2001; Mallela 2007) but also increased levels of disease (Littler and Littler 1995; Goreau et al. 1998). As such, given the critical importance of coralline algae to coral reef formation, continued assessment and monitoring surveys will allow a better understanding of regional disease and enable the development of mitigation and management strategies.
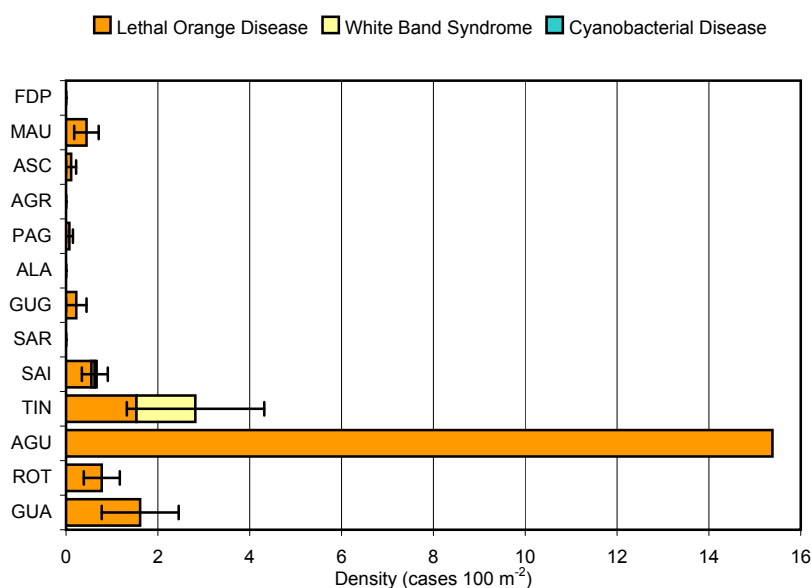
Figure 3.5.2a. Densities (cases 100 m^{-2}) of coralline-algal diseases from REA benthic surveys of forereef habitats conducted in the Mariana Archipelago during MARAMP 2007. Error bars indicate standard error (± 1 SE) of the mean.

3.6   Benthic Macroinvertebrates

3.6.1   Density Distribution: Giant Clams, Sea Urchins, and Sea Cucumbers

Based on towed-diver benthic surveys of forereef habitats averaged over the 3 MARAMP survey years, the archipelago-wide spatial patterns for density of giant clams suggest that densities generally were higher in the northern islands of the Mariana Archipelago than in the populated, southern islands (Fig. 3.6.1a). Maug had the greatest density of giant clams with 0.405 organisms 100 m^{-2} (SE 0.059), and the next highest estimate recorded at an island was 0.107 organisms 100 m^{-2} (SE 0.023) at Guguan. Anatahan had the lowest density of giant clams in this archipelago with 0.004 organisms 100 m^{-2} (SE 0.002). However, this result is not remarkable, given the extremely low visibility caused by volcanic ash in the water form eruptions of Anatahan Volcano that started in 2003 and continued through 2008. Of the surveyed offshore banks and remote reefs, Arakane and Pathfinder Reefs had the greatest densities of giant clams with 0.092 organisms 100 m^{-2} (SE 0.012) and 0.073 organisms 100 m^{-2} (SE 0.01). Among the 5 southern islands that were surveyed, uninhabited Aguijan had the greatest density of clams with 0.053 organisms 100 m^{-2} (SE 0.008). Densities at the remaining southern islands were low, relative to the rest of the Mariana Archipelago, with Guam having the lowest estimate of 0.006 organisms 100 m^{-2} (SE 0.001).

Figure 3.6.1a. Mean overall densities (organisms 100 m^{-2}) of giant clams from towed-diver benthic surveys of forereef habitats conducted in the Mariana Archipelago during MARAMP 2003, 2005, and 2007. Error bars indicate standard error (± 1 SE) of the mean.
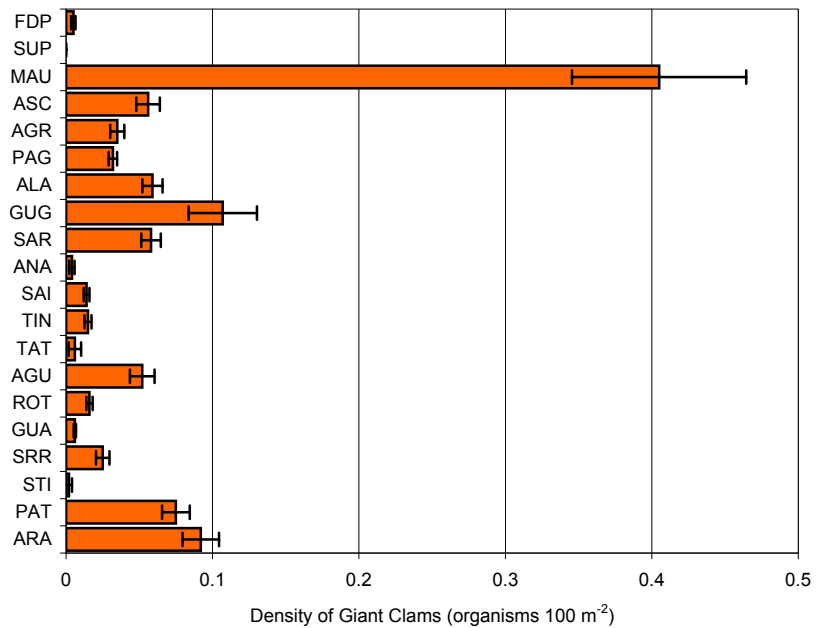
In contrast to densities of giant clams, the archipelago-wide spatial patterns for sea urchins suggest that daytime densities were higher in the southern islands than in the northern islands and that the remote Pathfinder and Arakane Reefs had the greatest densities of sea urchins observed in the Marina Archipelago (Fig. 3.6.1b) with 7.73 organisms 100 m^{-2} (SE 0.63) and 11.15 organisms 100 m^{-2} (SE 0.1). Rota and Tinian had the next highest densities of sea urchins with 5.39 organisms 100 m^{-2} (SE 0.48) and 4.54 organisms 100 m^{-2} (SE 0.63). Guam had the lowest density of sea urchins among the southern islands with 0.79 organisms 100 m^{-2} (SE 0.09). Compared to the densities recorded at the southern islands, excluding Guam, densities of sea urchins were low in the northern islands, except for at Maug and Pagan with 3.71 organisms 100 m^{-2} (SE 0.49) and 3.04 organisms 100 m^{-2} (SE 0.4).

Similar to the survey results for sea urchins, the southern islands of the Mariana Archipelago tended to have greater densities of sea cucumbers than did the northern islands (Fig. 3.6.1c), although Pagan had the highest daytime density of sea cucumbers in the Mariana Archipelago with 0.84 organisms 100 m^{-2} (SE 0.08). The surveyed remote reefs and offshore banks were nearly devoid of sea cucumbers with the exception of Tatsumi and Santa Rosa Reefs.

Figure 3.6.1b. Mean overall densities (organisms 100 m^{-2}) of sea urchins from towed-diver benthic surveys of forereef habitats conducted in the Mariana Archipelago during MARAMP 2003, 2005, and 2007. Error bars indicate standard error (± 1 SE) of the mean.
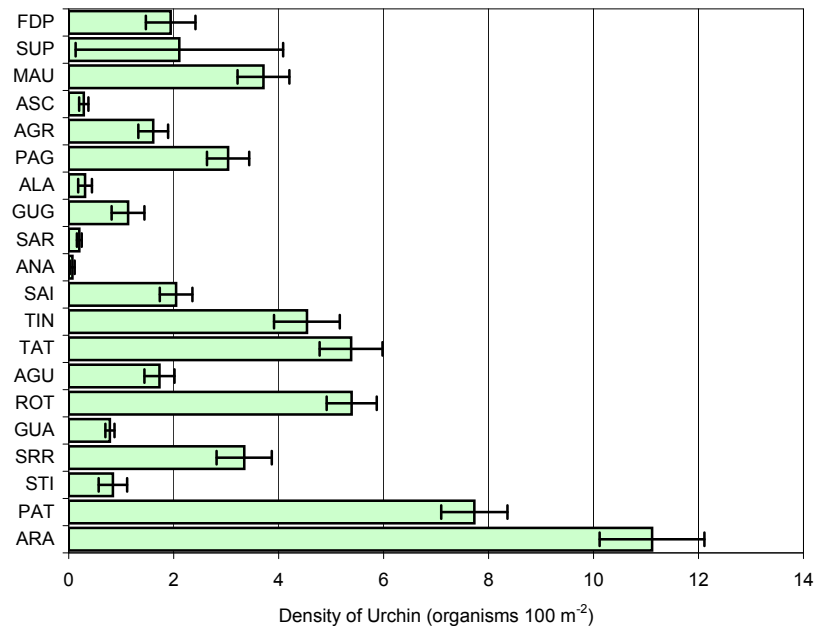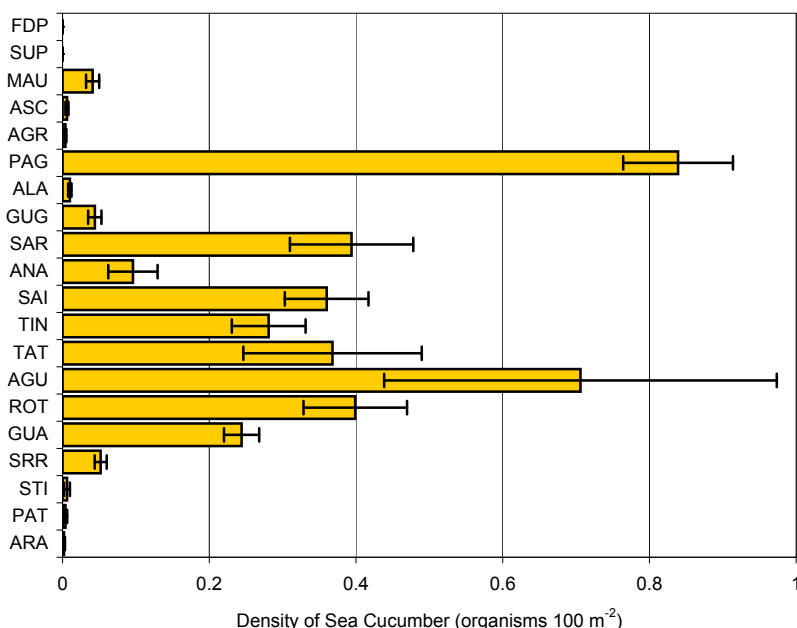
Figure 3.6.1c. Mean overall densities (organisms 100 m^{-2}) of sea cucumbers from towed-diver benthic surveys of forereef habitats conducted in the Mariana Archipelago during MARAMP 2003, 2005, and 2007. Error bars indicate standard error (± 1 SE) of the mean.

3.6.2   Species Richness: Sea Cucumbers and Sea Urchins

The archipelago-wide spatial patterns for species richness of macroinvertebrates based on REA benthic surveys of forereef habitats combined for the 3 MARAMP survey years suggest that daytime species richness for sea cucumbers was higher in the southern islands (55 total surveyed sites) than in the northern islands (104 total surveyed sites), but no spatial pattern was observed for sea urchins (Fig. 3.6.2a). In the Mariana Archipelago, during the 3 survey periods, 15 species of sea cucumbers (Table 3.6.2a) and 11 species of sea urchins (Table 3.6.2b) were identified.
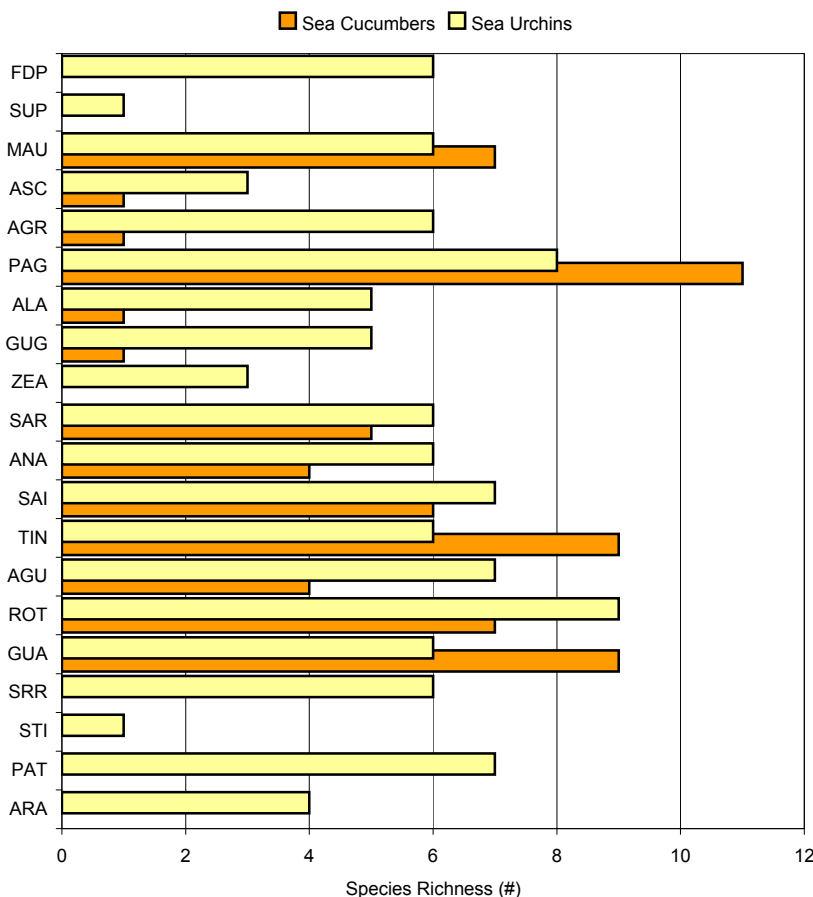
Figure 3.6.2a. Mean total species richness of sea cucumbers and sea urchins by island or bank from REA benthic surveys of forereef habitats conducted in the Mariana Archipelago during MARAMP 2003, 2005, and 2007.

As noted in the previous section, densities of sea cucumbers also were higher in the southern islands than in the northern islands (Fig. 3.6.1c). Among the southern islands, Aguijan had the greatest overall mean density of sea cucumbers from towed-diver benthic surveys but the lowest number of species observed during REA surveys (Fig. 3.6.2a). Low richness at Aguijan was likely a reflection of survey effort considering that only 5 sites were surveyed there. Conversely, Guam had the lowest density of sea cucumbers from towed-diver surveys conducted at the southern islands, but this island was one of the most species rich from REA surveys. The high richness found at Guam relates to the level of survey effort (18 surveyed sites), which was greater there than at other southern islands. Pagan, which had the second-highest survey effort in the Mariana Archipelago with 24 sites surveyed over 3 years, had the greatest observed diversity of sea cucumbers with 11 species identified. Only 1 species was observed at each of 4 islands nearest to Pagan: Alamagan and Guguan to the south and Agrihan and Ascuncion to the north. Of the 15 species of sea cucumbers recorded (Table 3.6.2a), 2 species, *Thelenota ananas* and *Holothuria fuscopunctata*, were not observed in the northern islands, while 2 species, *Actinopyga palauensis* and *Bohadschia marmorata*, were not observed in the southern islands.

Species richness of sea urchins was distributed fairly evenly across the Mariana Archipelago (Fig. 3.6.2a). The highest daytime species richness of sea urchins was found at Rota with 9 species recorded, followed by Pagan with 8 species observed. Of the 11 species recorded archipelago-wide, *Colobocentrotus atratus* was not observed in the southern islands and *Tripneustes gratilla* was not observed in the northern islands.

Table 3.6.2a. Species of sea cucumbers recorded at each island from REA benthic surveys of forer-eef habitats conducted in the Mariana Archipelago during MARAMP 2003, 2005, and 2007.

Island	*Actinopyga echinites*	*Actinopyga mauritiana*	*Actinopyga palauensis*	*Actinopyga sp.*	*Bohadschia argus*	*Bohadschia marmorata*	*Holothuria atra*	*Holothuria edulis*	*Holothuria fuscopunctata*	*Holothuria nobilis*	*Holothuria whitmaei*	*Pearsonothuria graeffei*	*Stichopus chloronotus*	*Stichopus horrens*	*Thelenota ananas*	Total
FDP																0
MAU		●		●	●		●	●					●	●		7
ASC											●					1
AGR		●														1
PAG	●	●	●		●	●	●			●	●	●	●	●		11
ALA		●														1
GUG		●														1
SAR		●									●	●	●	●		5
ANA		●			●		●						●			4
SAI		●			●		●	●					●	●		6
TIN		●	●				●	●	●	●		●	●		●	9
AGU		●			●		●						●			4
ROT		●			●		●				●	●	●		●	7
GUA	●			●	●		●	●			●		●	●	●	9

Table 3.6.2b. Species of sea urchins recorded at each island or bank from REA benthic surveys of forereef habitats conducted in the Mariana Archipelago during MARAMP 2003, 2005, and 2007.

Island	Colobocentrotus atratus	Diadema savignyi	Diadema sp.	Echinometra mathaei	Echinometra sp.	Echinostrephus aciculatus	Echinostrephus molaris	Echinothrix calamaris	Echinothrix diadema	Heterocentrotus sp.	Tripneustes gratilla	Total
FDP			●	●	●	●		●	●			6
SUP									●			1
MAU				●	●	●	●	●	●			6
ASC				●		●		●				3
AGR		●		●		●	●	●	●			6
PAG		●		●	●	●	●	●	●	●		8
ALA				●	●	●		●	●			5
GUG		●		●		●		●	●			5
ZEA						●		●	●			3
SAR	●	●		●		●		●	●			6
ANA		●		●		●	●	●	●			6
SAI		●	●	●	●	●		●	●			7
TIN		●	●	●	●	●			●			6
AGU				●		●		●	●	●	●	6
ROT		●	●	●	●	●	●	●	●	●		9
GUA		●		●		●		●	●			5
SRR		●		●		●		●	●			5
STI						●						1
PAT			●		●	●		●	●			5
ARA			●			●		●	●			4

3.6.3 Density Distribution: Crown-of-thorns Seastars

Densities of crown-of-thorns seastars (*Acanthaster planci*) from towed-diver benthic surveys of forereef habitats varied among geographic regions in the Mariana Archipelago and among the 3 MARAMP survey years. To facilitate discussion and visual representation of densities of crown-of-thorns seastars (COTS), means from towed-diver surveys were combined to produce density values for each geographic region defined around each island or bank (Figs. 3.6.3a–d). Understanding whether or not these densities signify an outbreak is important, since these corallivorous seastars can decimate a reef. By means of a manta-tow technique—which uses snorkel divers as observers in a manner similar to the procedure for MARAMP towed-diver surveys—Moran and De'ath (1992) defined a potential outbreak as a reef area where the density of *A. planci* was > 1500 organisms km^{-2} (0.15 organisms 100 m^{-2}) and the level of dead coral present was at least 40%. Using this definition only in terms of COTS density and considering each geographic region as an individual reef area, localized areas undergoing an outbreak were found during each MARAMP survey year.

During MARAMP 2003, the northern islands of the Mariana Archipelago were virtually devoid of COTS, with the exception of a potential small, localized outbreak in the west caldera region at Maug (Fig. 3.6.3a[A and B]). Meanwhile, COTS were abundant at all southern islands with the exception of Tinian (Fig. 3.6.3a[C]). The west region of Rota had a localized outbreak. The western shoreline of Guam, southern coast of Rota, and southeast region of Saipan all had densities that nearly met the definition of an outbreak; populations in these regions possibly were either growing into a potential localized outbreak or declining from one.
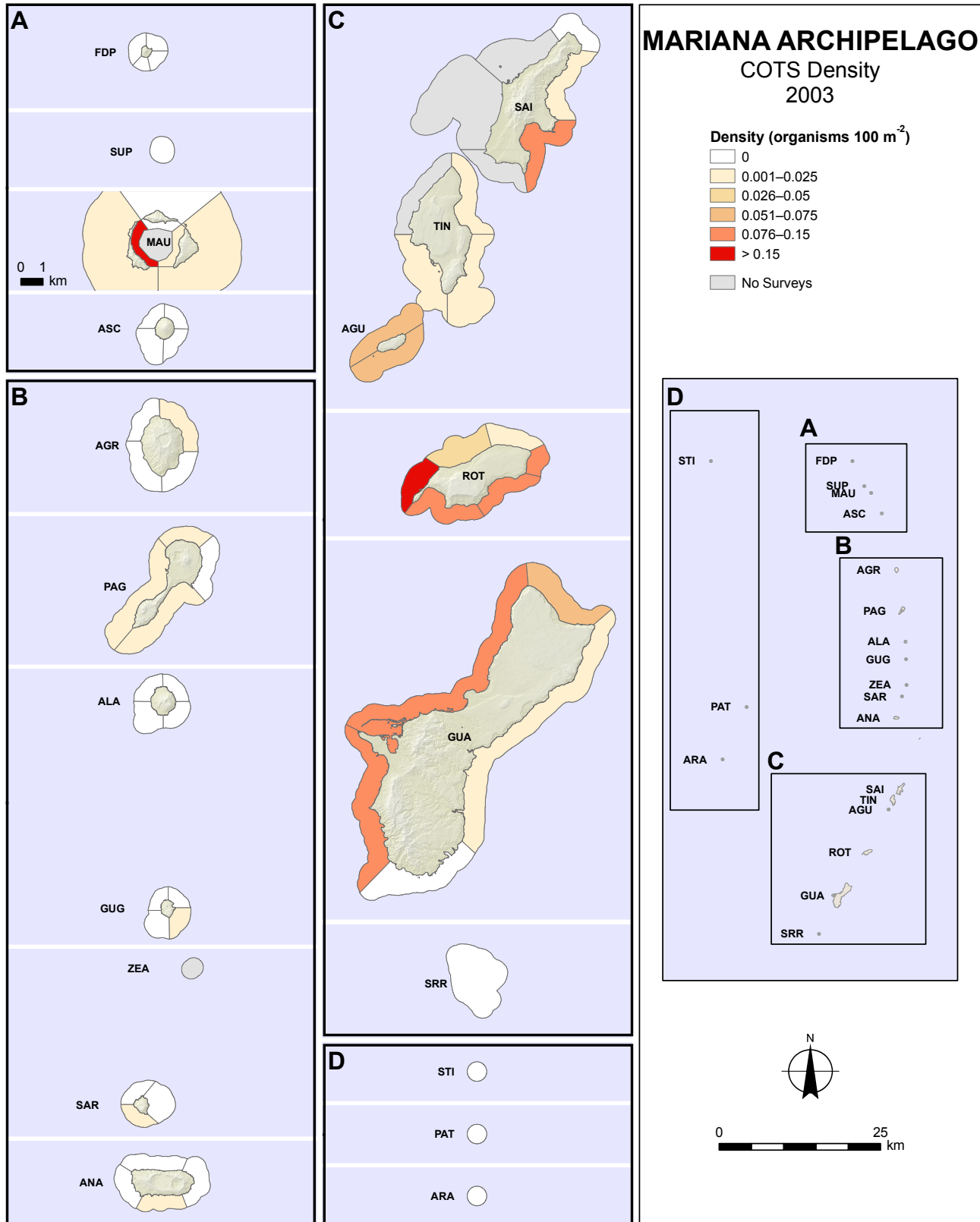
mean densities rose more than 100-fold from 0.002 organisms 100 m^{-2} (SE 0.001) in 2003 to 0.237 organisms 100 m^{-2} (SE 0.054) in 2005. Overall observed densities around Agrihan, Asuncion, and Guguan in 2003 were $\leq$ 0.01 organisms 100 m^{-2}; however, by 2005, islandwide mean densities for those islands had increased to 0.062 organisms 100 m^{-2}, (SE
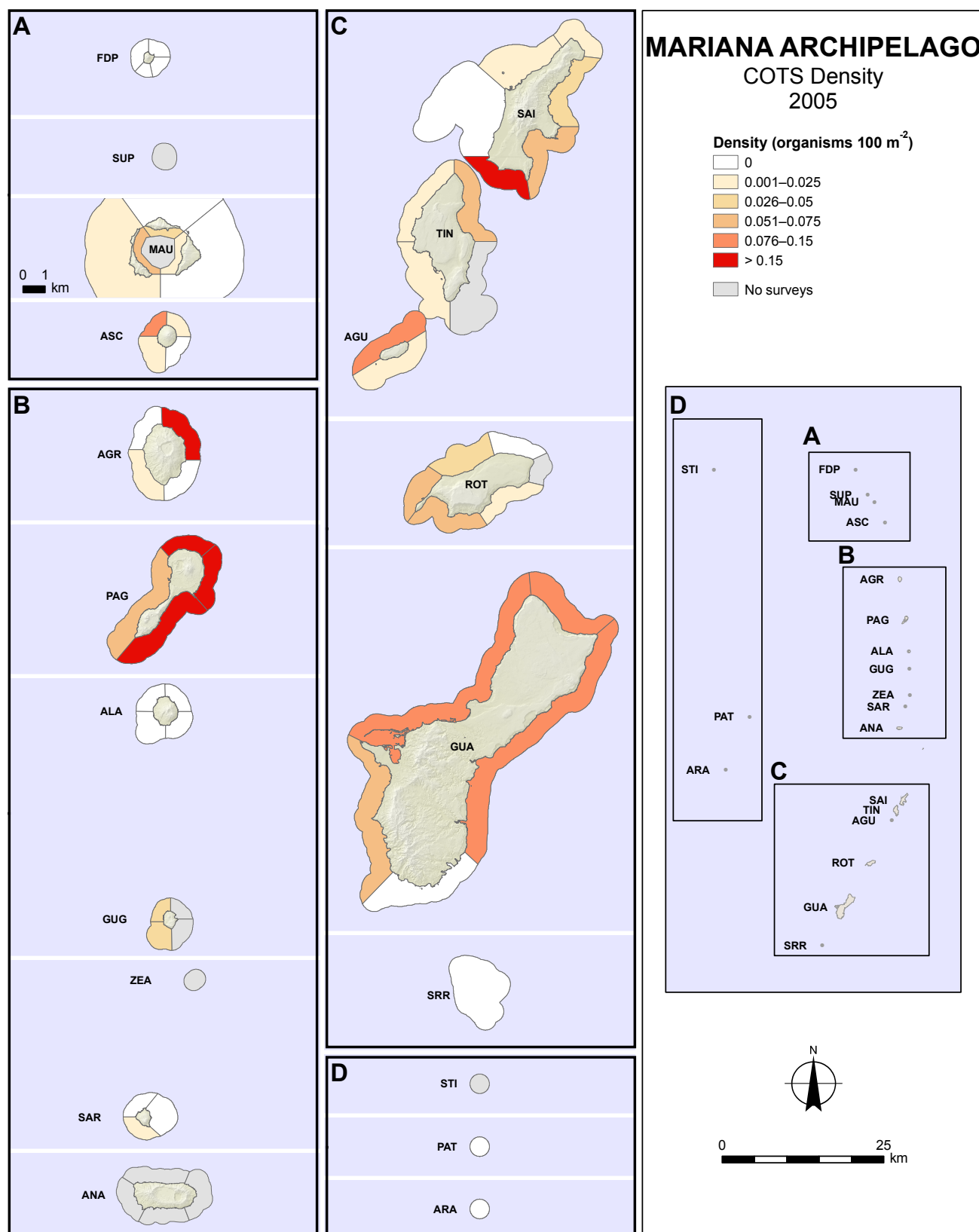
Figure 3.6.3b. Mean densities (organisms 100 m^{-2}) of COTS by geographic region from towed-diver benthic surveys of forereef habitats conducted in the Mariana Archipelago during MARAMP 2005.

0.028), 0.027 organisms 100 m^{-2} (SE 0.011), and 0.042 organisms 100 m^{-2} (SE 0.02). A decline in COTS populations between 2003 and 2005 was seen only at Maug, Sarigan, and Rota. At all the southern islands, except for Rota, most COTS populations remained relatively stable or increased slightly. Densities at Rota decreased nearly 3-fold from 0.106 organisms 100 m^{-2} (SE 0.014) to 0.037 organisms 100 m^{-2} (SE 0.006). Mean overall densities remained relatively stable at Agu-

Figure 3.6.3c. Mean densities (organisms 100 m^{-2}) of COTS by geographic region from towed-diver benthic surveys of forereef habitats conducted in the Mariana Archipelago during MARAMP 2007.

jian and Tinan between 2003 and 2005, but concentrations shifted to different areas. At Saipan, overall mean densities increased slightly from 0.046 organisms 100 m^{-2} (SE 0.035) to 0.063 organisms 100 m^{-2} (SE 0.017), and localized outbreaks were recorded in this island's southeast region in 2003 and south region in 2005 (Fig. 3.6.3b[C]). COTS densities at Guam increased from 0.049 (SE 0.015) to 0.098 organisms 100 m^{-2} (SE 0.027), and the locations of greatest COTS concentrations shifted. In 2003, the highest densities at Guam occurred along the western shoreline, but, in 2005, the highest densities were found in the east region, followed by the northwestern and north regions. This change suggests that a recruitment pulse took place along the eastern shore of Guam sometime between 2003 and 2005.

Figure 3.6.3d. Spatial and temporal comparison of mean densities (organisms 100 m^{-2}) of COTS from towed-diver benthic surveys of forereef habitats conducted in the Mariana Archipelago during MARAMP 2003, 2005, and 2007. Error bars indicate the standard error (± 1 SE) of the mean.
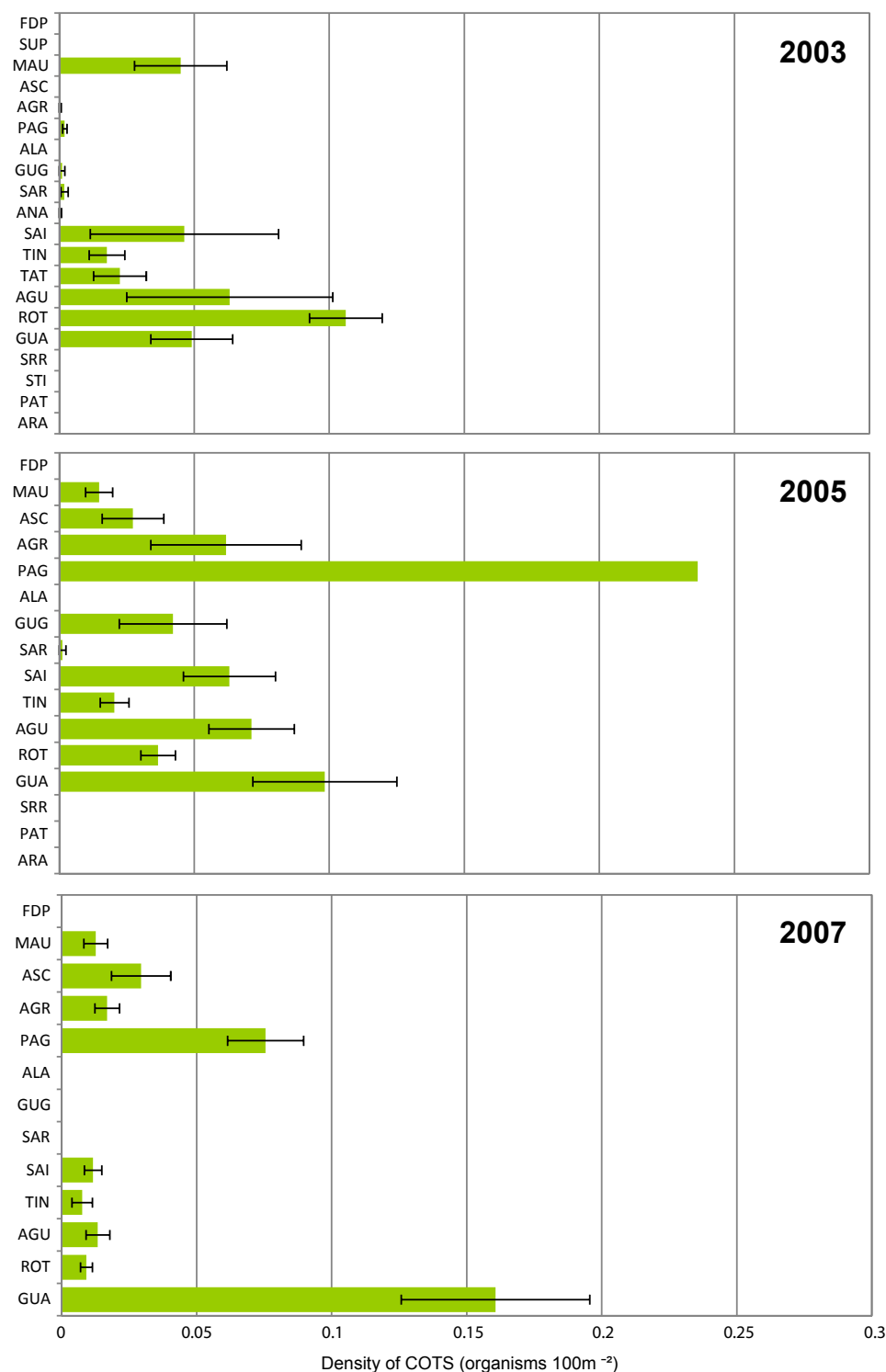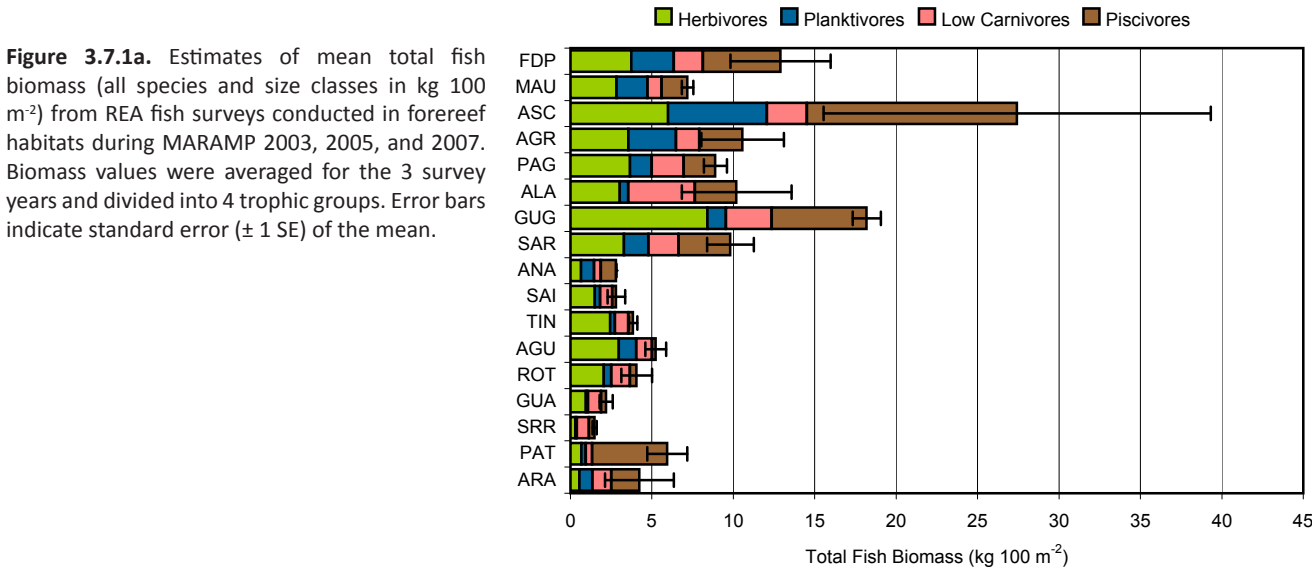
COTS densities recorded in the northern islands during towed-diver benthic surveys in the Mariana Archipelago were much lower in 2007 than in 2005 (Fig. 3.6.3c[A and B]). Densities observed around Pagan, Agrihan, and Guguan decreased 3-fold between MARAMP 2005 and 2007. Only around Asuncion was a slight increase (0.002 organisms 100 m^{-2}) in overall observed density recorded between 2005 and 2007. Likewise, COTS populations in the southern islands, except at Guam, decreased significantly by 2007 (Fig. 3.6.3c[C]). Densities increased by 60% around Guam from 0.098 organisms 100 m^{-2} (SE 0.027) in 2005 to 0.161 organisms 100 m^{-2} (SE 0.035) in 2007. Localized outbreaks were occurring along much of the eastern shoreline of Guam in 2007. This increase in density substantiates the idea that a recruitment pulse occurred along the eastern shore of this island sometime between 2003 and 2007. Since COTS densities naturally fluctuate with food availability and successful recruitment events (Birkeland and Lucas 1990; Fabricius et al. 2010; Yamaguchi 1987), the oscillation in this archipelago of population densities between the 3 MARAMP survey years is not extraordinary.

3.7   Reef Fishes

3.7.1   Reef Fish Surveys

Other than at Asuncion, where several reef sharks (Carcharhinidae) and large jacks (Carangidae) were seen in 2005 and 2007 but not in 2003, total fish biomass, calculated as weight per unit area, remained relatively stable in the Mariana Archipelago during the MARAMP survey period of 2003–2007. Annual means for the Mariana Archipelago, from REA fish surveys in forereef habitats, excluding Asuncion, ranged from 6.24 kg 100 m^{-2} to 8.17 kg 100 m^{-2}. Including Asuncion, annual means ranged from 7.38 kg 100 m^{-2} to 11.28 kg 100 m^{-2}. However, biomass levels differed greatly between sections of the Mariana Archipelago. Data from REA fish surveys suggest that the 9 northern islands, from Anatahan north to Farallon de Pajaros, as a group harbored more than 3 times the biomass of the 5 surveyed southern islands (Saipan, Tinian, Aguijan, Rota, and Guam), with total fish biomass of 12.00 kg 100 m^{-2} (SE 2.37) at northern islands and 3.63 kg 100 m^{-2} (SE 0.53) at southern islands (Fig. 3.7.1a). Observations from towed-diver surveys of large fishes (≥ 50 cm in total length [TL]) were dominated by piscivores, such as sharks and jacks. Results from these surveys of forereef habitats show a pattern similar to the one seen in data from REA surveys of fishes of all sizes with recorded biomass higher in the northern islands than in the southern islands (Fig. 3.7.1b): 0.92 kg 100 m^{-2} (SE 0.18) versus 0.22 kg 100 m^{-2} (SE 0.04). Similar broad patterns were seen in shark abundance from towed-divers surveys, with the number of sharks encountered per unit area surveyed 10 times higher in the northern islands, with 174.5 individuals km^{-2}, than in the southern islands, with 17.6 individuals km^{-2}.

Results from REA fish surveys suggest that biomass values for all trophic groups were higher in the northern islands than in the southern islands. These north–south differences, however, were greatest for piscivores, for which mean biomass around the northern islands, at 4.04 kg 100 m^{-2} (SE 1.22), was more than 13 times the mean biomass of 0.30 kg 100 m^{-2} (SE 0.03) around the southern islands. Overall, piscivores made up 34% of estimated biomass from REA fish surveys of northern islands but only 8% of biomass recorded at the southern islands. Fish assemblages at the southern islands were dominated by herbivores, which accounted for 54% of total biomass there (Fig. 3.7.1a). Still, biomass of herbivorous fishes, including

Figure 3.7.1a. Estimates of mean total fish biomass (all species and size classes in kg 100 m^{-2}) from REA fish surveys conducted in forereef habitats during MARAMP 2003, 2005, and 2007. Biomass values were averaged for the 3 survey years and divided into 4 trophic groups. Error bars indicate standard error (± 1 SE) of the mean.

surgeonfishes (Acanthuridae) and parrotfishes (Scaridae), was twice as high at the northern islands than at the southern islands. These patterns in total biomass and trophic composition are consistent with those found along anthropogenic gradients in other archipelagoes in the central Pacific (Williams et al. 2011; Stevenson et al. 2007; Friedlander et al. 2008; Friedlander and DeMartini 2002). As noted above, overall mean total biomass was highly variable at Asuncion. The low number of surveys conducted there, at 3 REA sites per year, meant that estimated total biomass for this island was heavily influenced by isolated sightings like the 6 large (> 100 cm in TL) giant trevally (*Caranx ignobilis*) recorded at a single REA site in 2007.
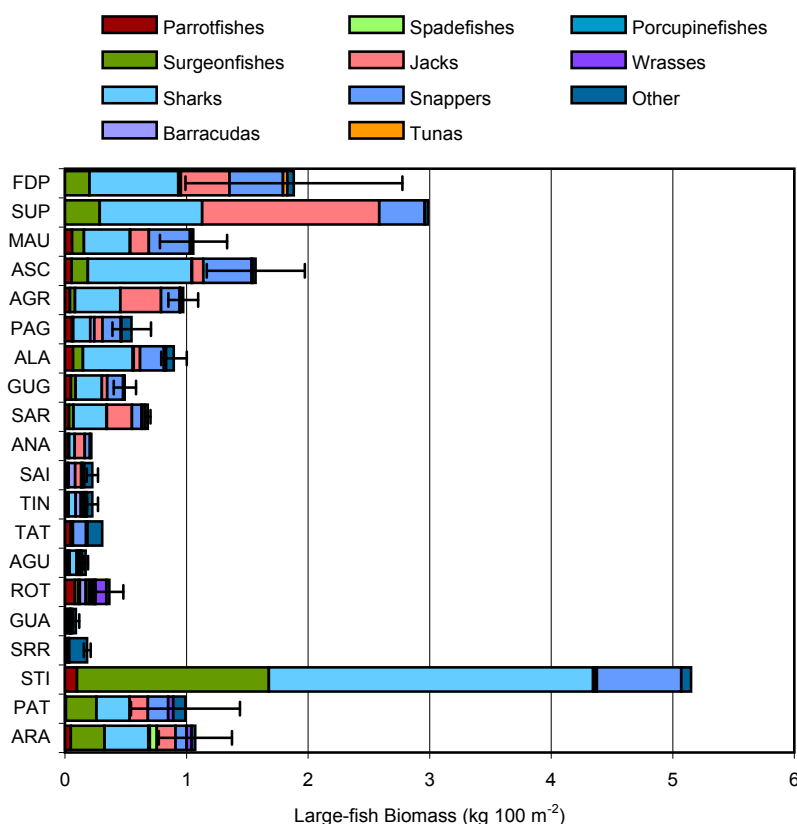
Figure 3.7.1b. Estimates of mean biomass (kg 100 m^{-2}) of large fishes (≥ 50 cm in total length) from towed-diver surveys of forereef habitats conducted during MARAMP 2003, 2005, and 2007. Large-fish biomass values were averaged for the 3 survey years and divided into 10 main family groups and an "Other" group. Error bars indicate standard error (± 1 SE) of the mean.

Summarized temporal trends (Fig. 3.7.1c) suggest relative stability in observed fish biomass in the southern islands of Guam, Rota, Saipan, Aguijan, and Tinian from both REA surveys of all fishes and from towed-diver surveys of large fishes. Estimated biomass at the northern islands, as a group, was more variable among years, with error bars much larger for the northern islands than for the southern islands, and relatively high variability among years. Both types of variability reflect-
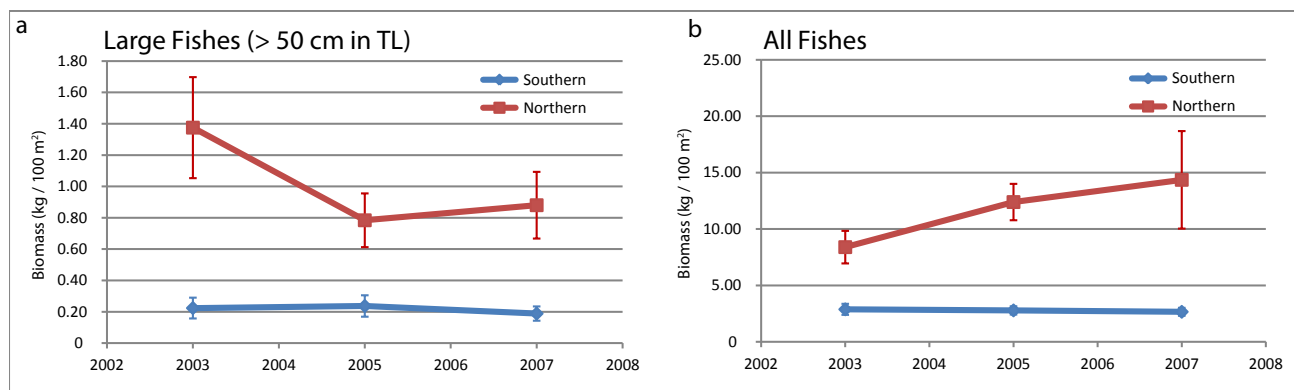
Figure 3.7.1c. Trends in fish biomass for (*a*) all fishes from REA surveys and (*b*) large fishes from towed-diver surveys at the northern islands and southern islands of the Mariana Archipelago. To increase comparability among regions and years, these graphs use only data from forereef habitats and from islands surveyed in each of MARAMP 2003, 2005, and 2007. Error bars indicate standard error (± 1 SE) of the mean.

ed the effect of occasional estimates of very high biomass in some surveys of northern islands (e.g., where several sharks or other large predators were seen in a single survey). Nevertheless, trends through time for MARAMP 2003, 2005, and 2007 pooled at this scale suggest that biomass was consistently higher at the northern islands than at the southern islands in all survey periods for both REA and towed-diver surveys, with between 3.3 and 6.1 times the biomass of large fishes and 2.9 to 5.4 times the biomass of all fishes combined in the northern islands versus the southern islands, depending on the year.

Figure 3.7.1d. Size-class distribution (TL in cm) for (*a*) groupers, (*b*) parrotfishes, and (*c*) surgeon-fishes from REA fish surveys of forereef habitats conducted at the 9 northern islands (from Ana-tahan north through Farallon de Pajaros) and 5 surveyed southern islands (Guam, Rota, Aguijan, Tinian, and Saipan) of the Mariana Archipelago during MARAMP 2007.
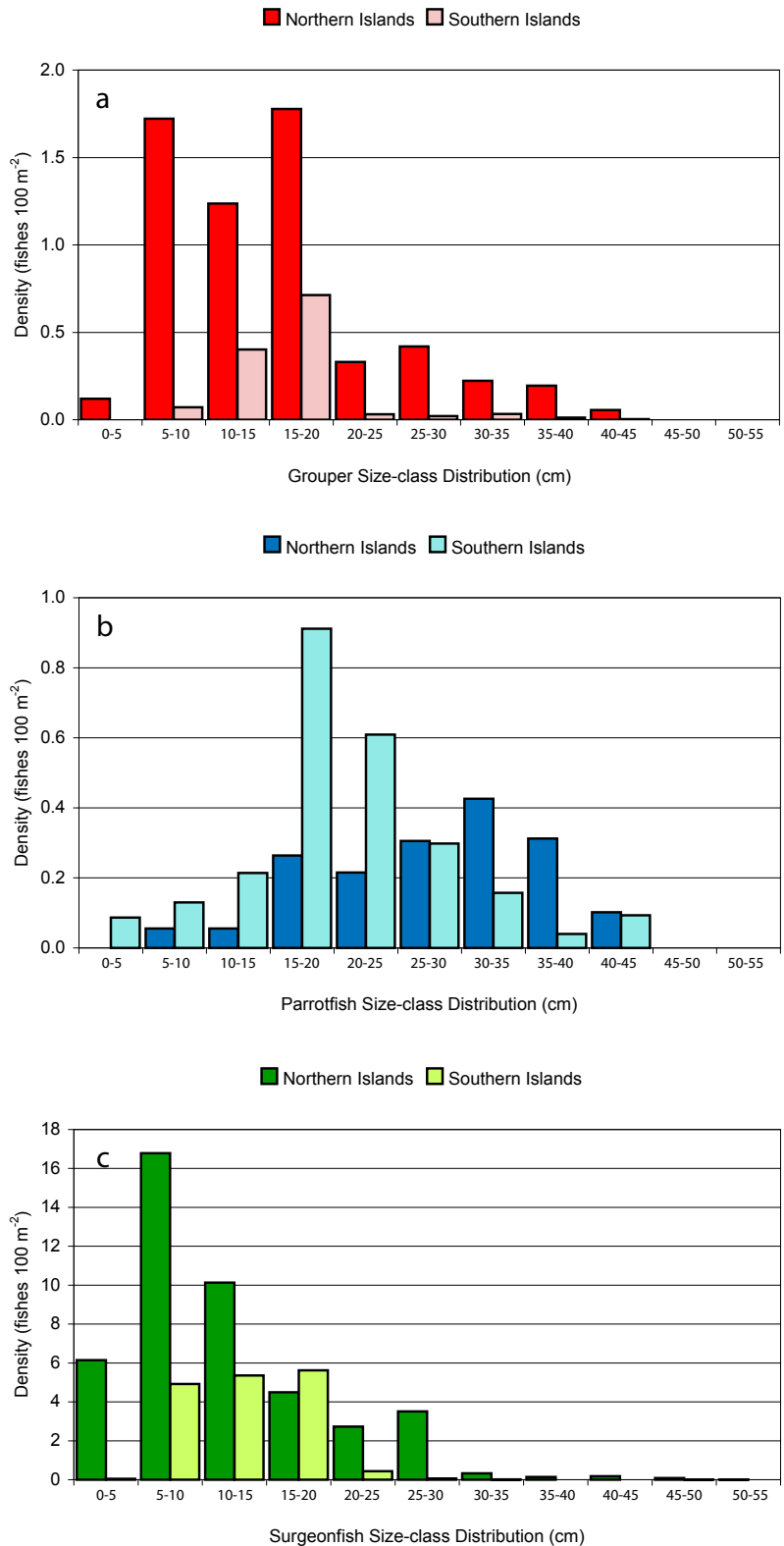
Observations of size-class distribution for 3 families of fishes from REA surveys conducted in 2007 in the Mariana Archipelago show that densities of large size classes were higher in the northern islands than in the southern islands (Fig. 3.7.1d). Groupers (Serranidae) of all size classes were more abundant in the northern islands. Size classes of fishes > 30 cm in TL were commonly encountered in the northern islands but rare in the southern islands. Parrotfishes displayed more of a bimodal distribution with large individuals more common in the northern islands and small individuals more common in the southern islands. Although the surgeonfish community was dominated by small size classes, the overall range of fish sizes was greater in the northern islands, where densities were higher for all but the size class of 15–20 cm.

Species richness, measured as the number of fish species encountered per 100 square meters and averaged across MARAMP 2003, 2005, and 2007, was higher in the northern islands, excluding Anatahan, with 30.6–43.6 species 100 m^{-2} than around the southern islands with 20.2–30.0 species 100 m^{-2} (Fig. 3.7.1e). Mean richness was very low at Anatahan in 2003, the one year that it was surveyed, with mean richness of 14.1 species 100m^{-2}, which may have been a consequence of low visibility caused by high amounts of ash and debris in the water from a recent volcanic eruption. The species diversity of fishes on Arakane Reef and Pathfinder Reef of the West Mariana Ridge and on Santa Rosa Reef south of Guam was rather low by archipelagic standards with mean richness of 23.5, 24.1, and 13.9 species 100 m^{-2} (Fig. 3.7.1e).
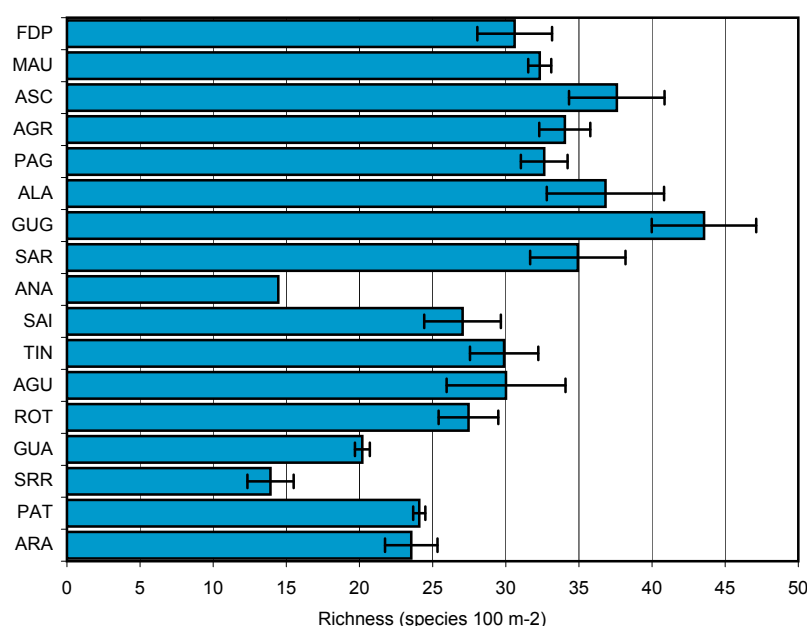
Figure 3.7.1e. Mean fish species richness (species 100 m^{-2}) from REA fish surveys conducted in the Mariana Archipelago during MARAMP 2003, 2005, and 2007. Error bars indicate standard error (± 1 SE) of the mean.

3.8   Species of Concern

Efforts to determine the status of species of concern—rare large fishes and sea turtles—in the Mariana Archipelago were made using data from towed-diver surveys of forereef habitats conducted during MARAMP 2003, 2005, and 2007. This section discusses the total mean abundance, measured as the number of individuals per square kilometer, of rare large fishes (≥ 50 cm in TL), and sighting frequency, measured as the number of individuals per kilometer, of sea turtles observed during MARAMP 2003, 2005, and 2007 (Tables 3.8a and b). All species identified are listed under the International Union for Conservation of Nature (IUCN) Red List with the grey reef shark (*Carcharhinus amblyrhynchos*), blacktip reef shark (*C. melanopterus*), and whitetip reef shark (*Triaenodon obesus*) listed as near threatened, the tawny nurse shark (*Nebrius ferruguenius*) and bumphead parrotfish (*Bolbometopon muricatum*) listed as vulnerable, the humphead wrasse (*Cheilinus undulatus*) and green sea turtle (*Chelonia mydas*) listed as endangered, and the hawksbill turtle (*Eretmochelys imbricata*) listed as critically endangered under the IUCN Red List Categories (Smale 2005a; Heupel 2005;. Smale 2005b; Pillans 2003; Chan et al. 2007; Russell 2004; Seminoff 2004; Mortimer and Donnelly 2008).

Based on averages from towed-diver surveys conducted during the 3 MARAMP survey periods, the abundance of reef sharks (Carcharhinidae) was highest at Stingray Shoal and generally higher at the islands from Alamagan north and at Supply and Pathfinder Reefs than at other areas in the Mariana Archipelago (Table 3.8a). Excluding locations that were sampled with fewer than 10 towed-diver surveys in total, the highest densities of reef sharks were observed at the more

northerly islands. Farallon de Pajaros, Maug, Asuncion, Agrihan, and Alamagan all had reef shark densities > 200 individuals km^{-2}. In contrast, all islands from Sarigan south to Guam had densities < 50 individuals km^{-2}. Similarly, nurse sharks (Ginglymostomatidae) were relatively abundant at the northernmost islands, from Sarigan north to Farallon de Pajaros, where mean abundance of tawny nurse sharks ranged from 9.5 individuals km^{-2} (SE 2.4) to 39.7 individuals km^{-2} (SE 23.7). Nurse sharks were rarely encountered around the southern islands, among which the greatest mean density of 1.6 individuals km^{-2} (SE 1.6) was recorded at Tinian.

In contrast to the patterns for sharks, humphead wrasse were most frequently encountered during towed-diver surveys conducted in the southern islands, with the highest mean density of 39.5 individuals km^{-2} (SE 9.1) recorded at Rota. Only one humphead wrasse was observed north of Alamagan during the 3 MARAMP survey periods, at Agrihan in 2003, strongly indicating that its abundance was very low in the northern part of this archipelago.

In total, only 2 bumphead parrotfish were observed during the 3 survey periods, both of them at Pagan in 2003, so data are insufficient to draw meaningful conclusions about the distribution patterns of this species, other than that it appears to be rare at shallow depths throughout the Mariana Archipelago.

Sea turtles (Cheloniidae) were tallied by towed divers whenever they were observed during a survey (i.e., recorded sightings were not limited to the 10-m swath or width of a towed-diver-survey area). Thus, estimates of turtle abundance are given as the number of turtles observed per kilometer of distance covered during surveys. By that measure, sea turtles were most frequently encountered in the southern islands, particularly at Tinian and Saipan (Table 3.8b), where mean encounter rates were 1.69 individuals km^{-1} (SE 0.13) and 1.12 individuals km^{-1} (SE 0.24). The lowest turtle abundance values were found at the remote and offshore reefs where turtles were rarely encountered; none at all were seen during towed-diver surveys conducted at Stingray Shoal, Pathfinder Reef, Supply Reef, Tatsumi Reef, and Santa Rosa Reef, and one was observed at Arakane Reef in 2003. While turtles were present on some of the banks where they were not observed during towed-diver surveys (e.g., a single turtle was seen during an REA survey at Supply Reef in 2003), the combined results of towed-diver surveys from MARAMP 2003 and 2005 suggest low turtle densities on the offshore and remote banks of the Mariana Archipelago (for additional analysis of sea turtle data from MARAMP 2003, see Kolinski et al. 2005).

Table 3.8a. Total mean abundance, or number of individuals observed per square kilometer, of rare large-fish (≥ 50 cm in TL) species from towed-diver surveys of forereef habitats conducted in the Mariana Archipelago during MARAMP 2003, 2005, 2007. Values in parentheses indicate standard error (± 1 SE) of the mean .

Island	Total Number of Surveys (all years)	Reef Sharks (Carcharhinidae)				Nurse Sharks (Ginglymostomatidae)	Wrasse (Labridae)	Parrotfishes (Scaridae)
		Gray reef shark (*Carcharhinus amblyrhynchos*)	Blacktip reef shark (*Carcharhinus melanopterus*)	Whitetip reef shark (*Triaenodon obesus*)	Total	Tawny nurse shark (*Nebrius ferrugineus*)	Humphead wrasse (*Cheilinus undulatus*)	Bumphead Parrotfish (*Bolbometopn muricatum*)
Farallon de Pajaros	16	114.4 (102.9)	0	140.5 (61.7)	254.9 (162.1)	39.7 (23.7)	0	0
Supply	1	304.6	0	203.1	507.7	0	0	0
Maug	36	167.2 (59.4)	0	97.4 (13.0)	264.7 (70.0)	9.5 (2.4)	0	0
Asuncion	16	295.3 (140.3)	39.0 (39.0)	60.0 (18.4)	394.4 (159.4)	32.2 (7.9)	0	0
Agrihan	23	138.0 (47.1)	4.5 (4.5)	59.6 (20.4)	202.0 (34.5)	19.0 (2.9)	1.5 (1.5)	0
Pagan	54	0	1.1 (1.1)	29.0 (4.1)	30.0 (4.6)	18.6 (6.4)	0	1.7 (1.7)
Alamagan	18	129.4 (17.1)	0	114.8 (45.2)	244.2 (56.0)	18.8 (12.1)	6.6 (6.6)	0
Guguan	14	41.6 (19.5)	3.2 (3.2)	55. 6 (2.1)	100.4 (17.6)	11.8 (7.5)	3.2 (3.2)	0
Sarigan	17	24.4 (24.4)	6.6 (6.6)	15.6 (3.7)	46.6 (18.4)	27.7 (9.8)	8.6 (4.7)	0
Anatahan	12	23.6	0	9.4	33.0	0	0	0
Saipan	39	5.6 (5.6)	1.9 (1.0)	0	7.6 (4.7)	0	6.7 (3.4)	0
Tinian	26	0	3.3 (3.3)	24.7 (10.7)	29.0 (13.2)	1.6 (1.6)	2.6 (2.6)	0
Tatsumi	2	0	0	0	0	0	0	0
Aguijan	13	0	26.1 (11.4)	10.6 (10.6)	36.7 (7.1)	0	0	0
Rota	33	0	5.4 (3.3)	5.5 (1.0)	10.9 (4.3)	0	39.5 (9.1)	0
Guam	62	0.7 (0.7)	2.0 (2.0)	2.1 (1.2)	4.8 (2.9)	1.3 (1.3)	5.5 (0.8)	0
Santa Rosa	6	0	0	0	0	0	0	0
Stingray	4	1312.6	0	121.2	1433.8	0	0	0
Pathfinder	7	93.8 (12.6)	0	138.1 (8.3)	231.9 (20.9)	0	8.1 (8.1)	0
Arakane	9	12.4 (3.0)	0	72.9 (35.3)	85.3 (38.4)	4.7 (4.7)	9.4 (9.4)	0

Island	Total Number of Surveys (all years)	Sea Turtles (Cheloniidae)	
Farallon de Pajaros	16	0.20	(0.04)
Supply	1	0	
Maug	36	0.30	(0.04)
Asuncion	16	0.25	(0.15)
Agrihan	23	0.33	(0.10)
Pagan	54	0.34	(0.02)
Alamagan	18	0.52	(0.27)
Guguan	14	0.40	(0.20)
Sarigan	17	0.54	(0.24)
Anatahan	12	0.61	
Saipan	39	1.12	(0.24)
Tinian	26	1.69	(0.13)
Tatsumi	2	0	
Aguijan	13	0.35	(0.07)
Rota	33	0.66	(0.24)
Guam	62	0.61	(0.11)
Santa Rosa	6	0	
Stingray	4	0	
Pathfinder	7	0	
Arakane	9	0.05	(0.05)

Table 3.8b. Total mean sighting frequency, or number of individuals observed per kilometer, of sea turtles from towed-diver surveys of forereef habitats conducted in the Mariana Archipelago during MARAMP 2003, 2005, 2007. Values in parentheses indicate standard error (± 1 SE) of the mean.

3.9   Marine Debris

3.9.1   Marine Debris Surveys

Temporal comparisons of qualitative observations of marine debris made across the Mariana Archipelago are limited because debris sightings were recorded differently among MARAMP survey years (for information about technique changes and data limitations, see Chapter 2: "Methods and Operational Background," Sections 2.4.2: "Overview of Towed-diver Surveys" and 2.4.10: "Marine Debris"). Nonetheless, several observations from spatial comparisons remain notable.

A broad, archipelagic pattern was evident from spatial comparison of MARAMP towed-diver surveys, namely that overall abundance of marine debris generally was greater at the southern, populated islands of the Mariana Archipelago than at the sparsely populated or unpopulated northern islands (Fig. 3.9.1a). The abundance of derelict fishing gear and other man-made objects, based on the mean number of sightings recorded during the 3 MARAMP survey periods, was higher at Guam and Tinian than at other islands in the Mariana Archipelago. However, looking at values for single survey years and only for derelict fishing gear, Maug had the second-highest abundance of derelict fishing gear in 2003 with 7 net sightings recorded and the highest abundance in 2007 with 4 net sightings documented, and Farallon de Pajaros had the greatest abundance of derelict fishing gear in 2005 with 4 net sightings recorded and the third-highest abundance in 2007 with 2 net sightings documented. The high numbers of sightings of derelict fishing gear at these northernmost islands despite their remote location, relative to survey results at other islands in this archipelago, could indicate a number of effects from oceanographic influences to unidentified fishing pressures.

Sightings of derelict fishing gear, generally around the Mariana Archipelago, were dominated by identifications of small nets, net fragments, or lines, with larger nets reported only occasionally (e.g., near Cocos Island off Guam). Other man-made objects encountered during towed-diver surveys consisted largely of anchors and associated ground tackle, discarded or abandoned mooring blocks, or metal scrap. Sightings of munitions were rare, with 1 sighting recorded at Saipan in both 2005 and 2007 and 1 sighting of 15 clustered munitions identified off the airport runway at Tinian in 2007. Shipwreck sightings also were rare, with 2 sightings each noted at both Pagan and Rota in 2003 and 1 sighting each recorded at Pagan, Rota, and Tinian in 2007.

Several sightings of marine debris remained consistent between 2005 and 2007. These observations included a munitions sighting off the northwestern shore of Saipan, a shipwreck sighting off the south coast of Rota, and a sighting of an apparent dump site at Tinian in the vicinity of Puntan Lamanibot Sanhilo. In both 2003 and 2007, a shipwreck was identified near Bandera Peninsula at Pagan.

Figure 3.9.1a. Spatial and temporal comparison of mean numbers of sightings of specific types of marine debris from towed-diver benthic surveys of forereef habitats conducted in the Mariana Archipelago during MARAMP 2003, 2005, and 2007.
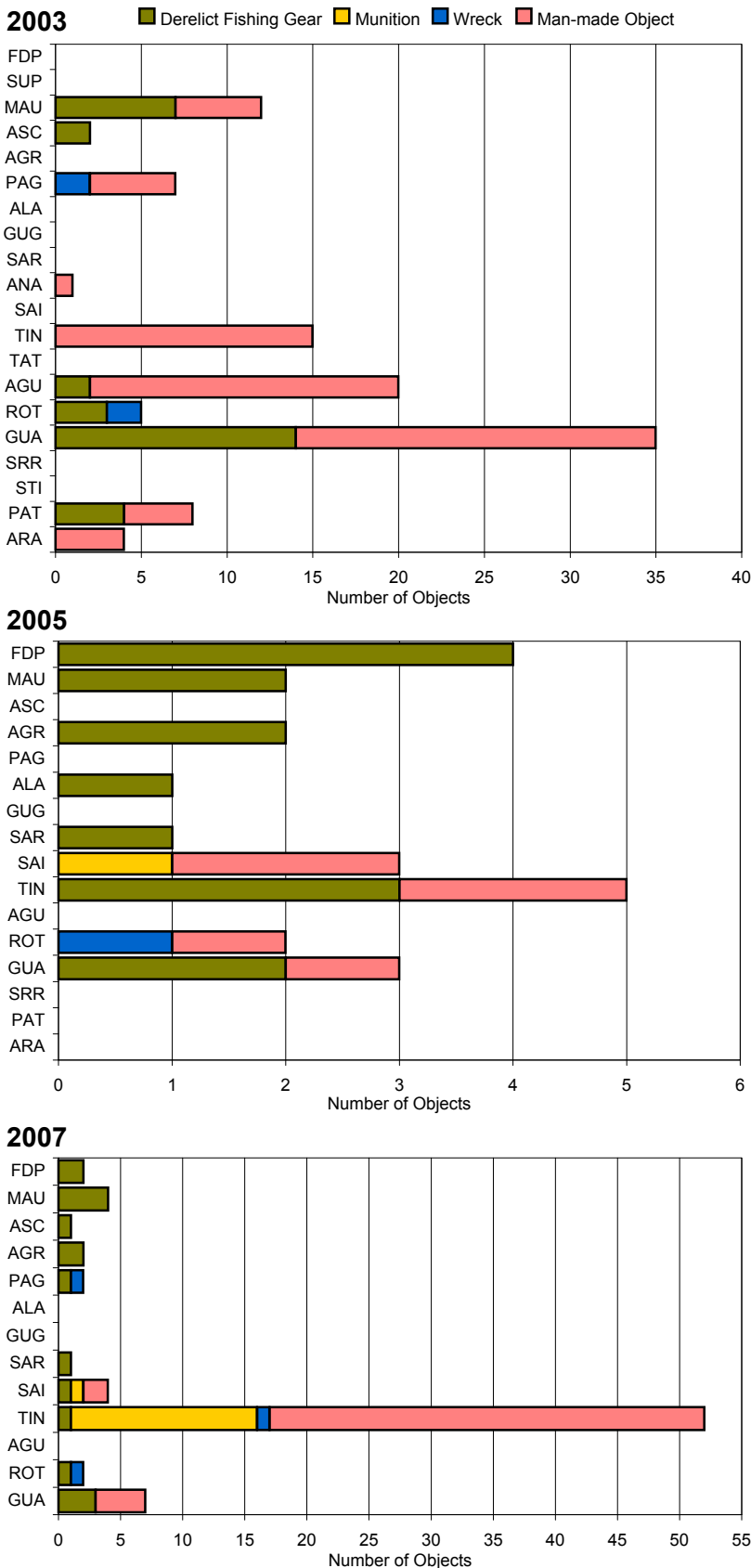
3.10   Ecosystem Integration

To compare the status of coral reef ecosystems across the Mariana Archipelago, CRED developed the *Archipelagic Coral Reef Condition Index*, a composite metric of biological variables from towed-diver surveys of forereef habitats conducted during MARAMP 2005 and 2007. Two other composite metrics make up this index: the *Archipelagic Benthic Condition Index* and *Archipelagic Fish Condition Index*. These indices integrate multiple components to describe benthic and reef-fish communities, either independently or together, and provide a simple means to evaluate the relative condition of different coral reef areas. The 5 benthic components are cover of live hard corals, cover of stressed corals, cover of macroalgae (both calcified and fleshy), cover of crustose coralline red algae, and density of COTS. The density and biomass of large fishes ($\geq$ 50 cm in TL) are the 2 fish components. The ranks in these condition indices, for the purposes of discussion and visual representation, are grouped as high, medium, or low. A high rank means superior condition relative to other geographic regions in the Mariana Archipelago, typically characterized by high cover values of hard corals and crustose coralline red algae, high levels of fish density and biomass, and low values of stressed-coral cover, COTS density, and macroalgal cover (Fig. 3.10a). A low rank indicates that a geographic region, relative to estimates from others regions in this archipelago, have low values of coral cover, crustose-coralline-red-algal cover, and fish density and biomass and high levels of stressed-coral cover, COTS density, and macroalgal cover. Data from towed-diver surveys were rank-transformed and integrated into these weighted, additive indices (see Chapter 2:"Methods and Operational Background" for towed-diver-survey field techniques and details about condition index methods, and see Appendix D for the ranks of each biological component for each geographic region). Spatial patterns in benthic, fish, and overall coral reef index ranks are presented in this section in maps by geographic region for the Mariana Archipelago (Figs. 3.10b, c, and d).

Figure 3.10a. Diagram showing the benthic and fish components and the directions of their ranks used in the Coral Reef Condition Index. CCA: crustose coralline red algae. High coral cover, for example indicated with a large green symbol, can result in a high rank.

The benthic conditions of geographic regions in the Mariana Archipelago in 2005 and 2007 generally decreased from the northernmost islands to the southern islands (Fig. 3.10b). The 2005 and 2007 ranks in the Archipelagic Benthic Condition Index indicate that the benthic conditions of forereefs around Maug, Alamagan, Sarigan, and Guguan were superior to the status of forereefs observed at other islands, a result of high or increasing levels of coral cover and low values of stressed-coral cover and COTS density. Although the benthic conditions of Asuncion and Farallon de Pajaros were also favorably ranked, certain geographic regions around these islands had lower index ranks for 2007 than for 2005 because of a decrease

Figure 3.10b. The Archipelagic Benthic Condition Index for 2005 and 2007, based on towed-diver surveys of forereef habitats, reflects the status of the benthic communities for each geographic region, *relative to other regions across the Mariana Archipelago*. The red color, for example, indicates a geographic region, such as the northeast region of Tinian during MARAMP 2005, with high index ranks that typically result from high cover values of corals and crustose coralline red algae and high levels of COTS densities and stressed-coral and macroalgal cover.

in cover of corals and crustose coralline red algae. A similar pattern of variable trends in benthic conditions was observed at Pagan and Agrihan, where geographic regions with high COTS densities had declining ranks. The benthic conditions for the northwest regions of Agrihan and Alamagan were consistently superior with high ranks for both survey years.

At the southern islands of Saipan, Tinian, Aguijan, Rota, and Guam, similar or decreasing benthic conditions were observed in most reef areas surveyed, except for the southeast region of Saipan, northeast region of Tinian, the west side of Rota, and the north region of Guam. The lower benthic index ranks for these islands, compared to the status for the northern islands, reflect relatively high levels of stressed-coral cover and macroalgal cover and low levels of coral cover.

The Archipelagic Fish Condition Index (Fig. 3.10c) demonstrates a north–south pattern of decreasing ranks for geographic regions in the Mariana Archipelago similar to the one seen for 2005 and 2007 in the Archipelagic Benthic Condition Index. However, this index shows a more stable temporal trend between MARAMP survey years. Maug, Asuncion, and Alamagan consistently had the best-ranking large-fish conditions in the Mariana Archipelago in 2005 and 2007 (Ranks for Farallon de Pajaros were high only for 2007). Geographic regions of the other northern islands, Agrihan, Pagan, Guguan, and Sarigan, had a mix of medium ranks in the Fish Condition Index. The southern islands generally had inferior ranks or decreasing large-fish conditions, although 1–2 geographic regions improved in rank at Saipan, Tinian, and Rota.

The Archipelagic Coral Reef Condition Index for geographic regions of the Mariana Archipelago illustrates a general decrease in benthic and large-fish conditions from the northern islands to the southern islands (Fig. 3.10d). Maug, Farallon de Pajaros, Alamagan, and Asuncion had the highest ranks in the Archipelagic Coral Reef Condition Index, resulting from high levels of coral cover and large-fish density and biomass and from low levels of stressed-coral cover. Ranks for most of the geographic regions around Agrihan varied because of high COTS densities and decreasing values of coral cover, particularly in the northeast region. The regions of the southern islands of Guam, Rota, Aguijan, Tinian, and Saipan generally had low or decreasing coral reef conditions, relative to conditions observed in the regions of other islands, with the exceptions of the east region of Saipan, where the rank changed from low to high from 2005 to 2007, and the northwest and southeast regions of Tinian and the north region of Aguijan, each of which had ranks of medium for 2007. Habitat protection and limitations on resource use in marine protected areas on the east side of Saipan might be a factor in the enhanced coral reef conditions there.

The Archipelagic Coral Reef Condition Index and the associated benthic and fish indices (Figs. 3.10b–d) all illustrate striking differences in the conditions of benthic and fish communities: ranks in derived condition indices declined moving from the northern islands to the southern islands. These spatial patterns coincide with patterns in human population, island geology, and latitude. A temporal comparison of ranks in the Archipelagic Coral Reef Condition Index demonstrates the stability of the spatial trends between the 2 MARAMP survey periods: approximately two-thirds of the index ranks (high, medium, or low) were the same in 2005 and 2007. The other one-third of geographic regions, then, may have been areas of change identified by the shift in their index ranks between years.

It is important to note that because of differences in geomorphology, as well as in exposure to typhoons and other acute and impactful physical disturbances, it is likely that coral reef ecosystems differed naturally between the northern and southern islands. Differences in the mix of benthic characters observed at southern reefs do not necessarily imply that those reefs were degraded only because of human activities. The carbonate, southern islands, for example, may naturally experience conditions that promote higher macroalgal growth than the growth seen in the volcanic, northern islands.

In another temporal comparison, the ranges in values of the biological components used in the condition indices were generally consistent between MARAMP 2005 and 2007 for all geographic regions, with slight declines in the maximum values observed for coral cover, macroalgal cover, COTS density, stressed-coral cover, and large-fish density (Table 3.10a). In addition, the maximum observed values of crustose-coralline-red-algal cover and large-fish biomass increased slightly.

MARIANA ARCHIPELAGO

Archipelagic Fish Condition Index
2005 and 2007

Fish Rank
No Surveys

High (1–12)
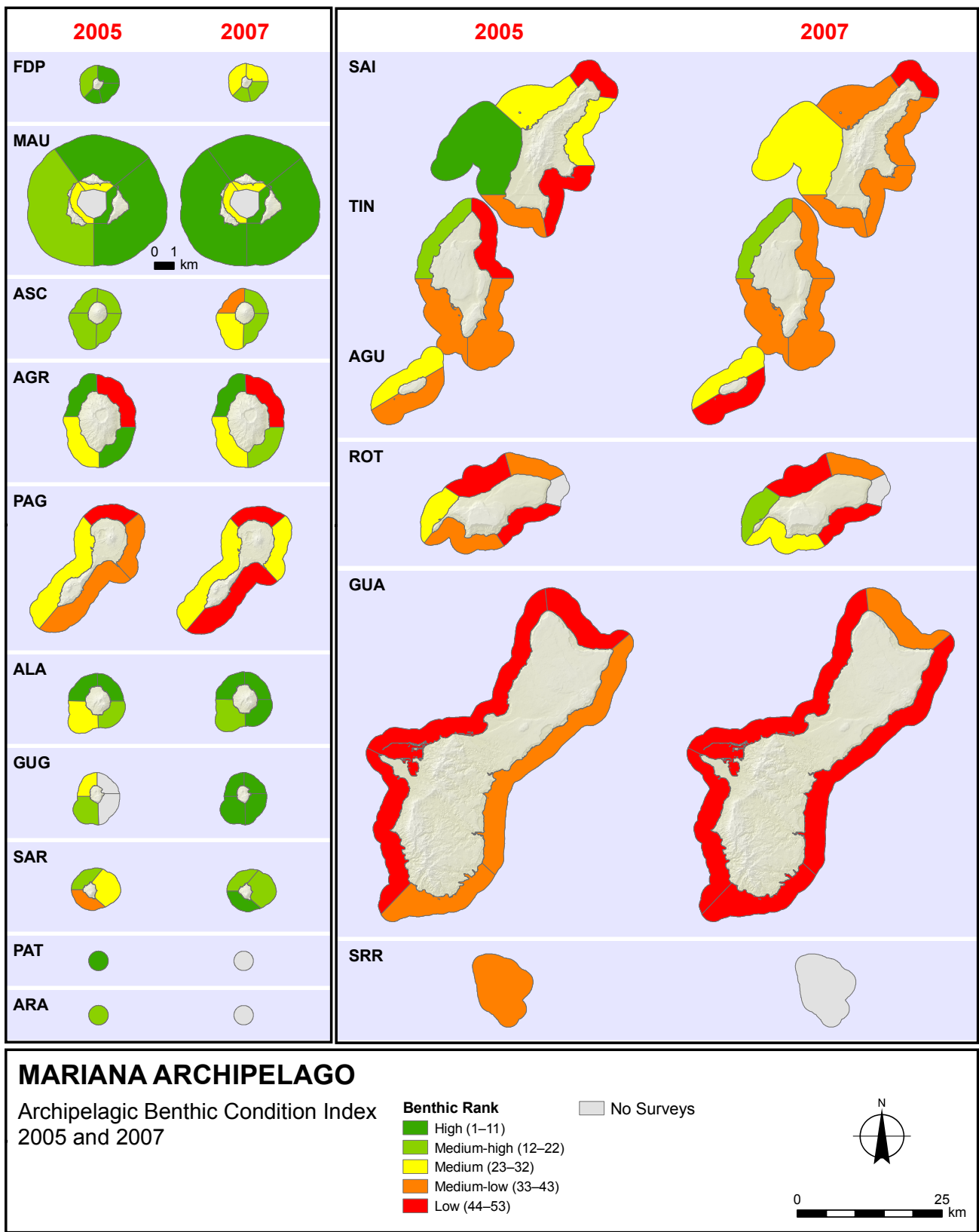Medium-high (13–23)
Medium (24–34)
Medium-low (35–45)
Low (46–56)
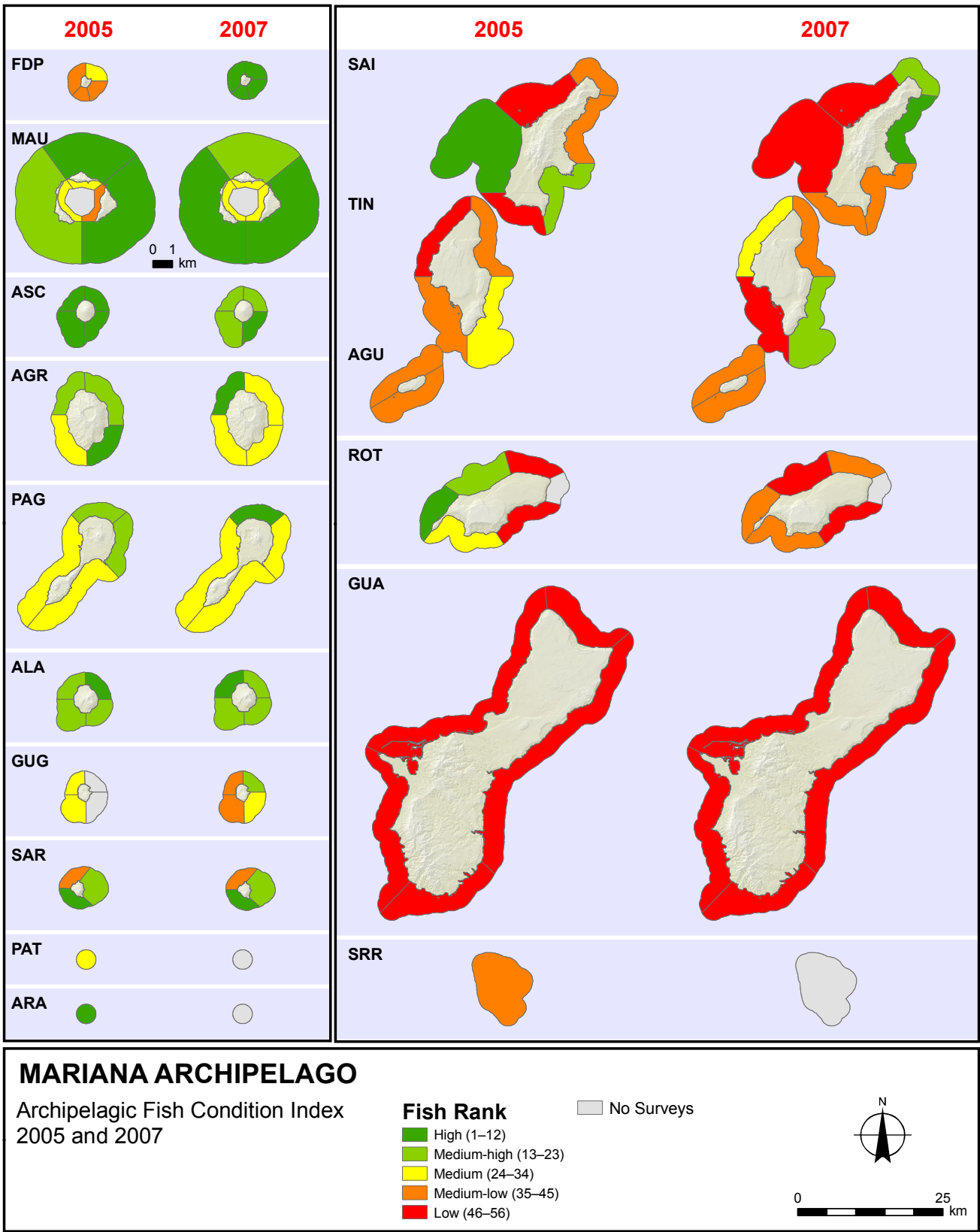
Figure 3.10c. The Archipelagic Fish Condition Index for 2005 and 2007, based on towed-diver surveys of forereef habitats, reflects the status of the benthic communities for each geographic region, *relative to other regions across the Mariana Archipelago*. The bright green color, for example, indicates geographic regions, such as the regions around Farallon de Pajaros during MARAMP 2007, with high index ranks that typically result from high fish density and biomass.
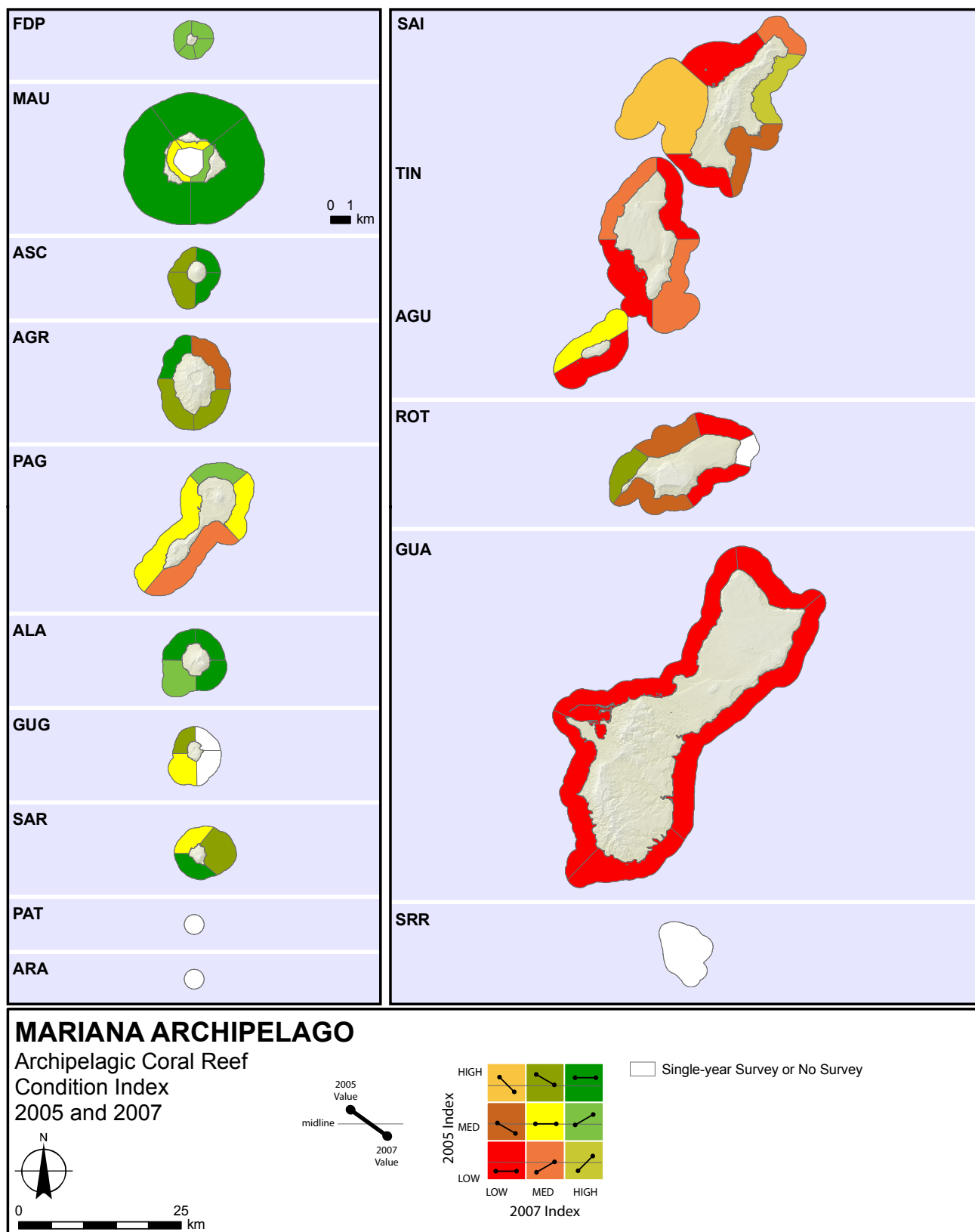
Figure 3.10d. The Archipelagic Coral Reef Condition Index, based on towed-diver surveys of forereef habitats conducted in 2005 and 2007, reflects the integrated condition of the benthic and fish communities for each geographic region, *relative to other regions across the Mariana Archipelago*. These maps indicate changes in index ranks between MARAMP 2005 and 2007 for each region. No index value is calculated for areas with only one year of survey data. A high rank means superior condition relative to other regions in this archipelago. The regions around Maug, for example, have high index ranks for both 2005 and 2007. Thus, they are all assigned the bright-green color that corresponds to the top-right square in the legend. The position of the horizontal bar above the midline in this square also reflects that those regions maintained a high rank in both years.

Table 3.10a. The ranges in mean values for geographic regions of the components used in the condition indices and measured during towed-diver surveys of forereef habitats in the Mariana Archipelago during MARAMP 2005 and 2007.

Year	Cover of Live Hard Corals (%)	Cover of Crustose Coralline Red Algae (%)	Cover of Stressed Corals (%)	Cover of Macroalgae (%)	Density of Crown-of-thorns Seastars (organisms 100 km^{-2})	Density of Large Fishes (individuals km^{-2})	Biomass of Large Fishes (kg 100 m^{-2})
2005	0.5–38	0.1–31.3	0–24.2	0.6–70.8	0–0.54	0.04–3.18	0.14–5.09
2007	0.8–31	0–34.2	0–14.4	1.5–60.1	0–0.34	0.04–1.42	0.19–4.69

3.11   Summary

Archipelagic comparisons of the biotic and abiotic constituents of coral reef ecosystems across the Mariana Archipelago revealed complex, north–south spatial patterns coupled with physical, oceanographic, environmental, and human dimensions. The islands of Guam, Rota, Tinian, and Saipan at the southern end of the Mariana Archipelago support more than 99% of the human population in this region. Consequently, urbanization on these islands has resulted in gradients of anthropogenic use and effects, including construction, deforestation, pollution, erosion, recreational use, and fishing.

The 5 southern islands and associated offshore banks surveyed as part of MARAMP share a common geological origin that consists of extinct volcanoes formed 15–20 million years ago and covered by layered carbonate formations. Except for uninhabited Aguijan, these southern islands are the largest islands in the Mariana Archipelago, with land areas of 85–544 km², and they are typically characterized by low to moderate slopes (means of ~ 10° on the seafloor) and flat-lying, step-like limestone terrains and karst topographies. However, southern Guam is atypical in that the volcanic terrain is not covered by carbonate terraces.

Oceanographically, the north–south orientation of the Mariana Archipelago results in latitudinal gradients in seasonal climatologies for SST, wind, currents, and Chl-*a*, with the southern islands exhibiting warmer SSTs, stronger wind conditions and surface currents, and less productive waters, when compared to the northern islands. Not surprisingly, because of natural and human-induced coastal processes, considerable spatial and temporal variability in water-quality parameters, including inorganic nitrogen and Chl-*a*, was observed from water samples collected in nearshore waters around the southern islands, particularly around Guam.

The shallow (depths of < 30 m) areas of potential benthic habitat are larger around the populated, southern islands than around the northern islands. These greater shallow reef areas support a wider range of habitat types and oceanographic conditions. Likely an effect of this greater variety in environments, benthic assemblage diversity—measured as total and mean generic richness of corals and macroalgae, as observed during REA benthic surveys of hard-bottom, forereef habitats—was greater for islands at the southern end of the Mariana Archipelago. Across the 3 MARAMP survey periods combined, the greatest total number of coral genera was recorded at Saipan with 38 genera enumerated, while the highest diversity of macroalgae was observed at Guam with 54 genera documented. Within this context, some coral taxa were restricted to and some algal taxa were particularly widespread in the southern islands, compared to survey results for the northern islands. These taxa included the hard corals *Diploastrea*, *Plesiastrea*, *Alveopora*, and *Coscinaraea* and the red algae *Amansia*, *Crouania*, *Gelidiella*, *Haloplegma*, *Halymenia*, and *Predaea*. Substrate type (carbonate versus basalt), habitat diversity, productivity, and life history are among the potential determinants of geographical patterns in species distribution.

The greater algal richness observed during REA benthic surveys among the populated, southern islands, versus the northern islands, was coupled with higher levels of mean macroalgal cover recorded on forereef habitats during broad-scale towed-diver benthic surveys in 2005 and 2007 and REA benthic surveys in 2007. Densities of sea urchins also were generally greater around the southern islands, as were species richness and densities of sea cucumbers. Estimates of live coral cover were variable spatially and temporally, and a north–south pattern for live coral cover was less clear than the one seen for macroalgal cover. Still, looking at survey results for REA and towed-diver benthic surveys conducted in 2007, cover levels generally were lower in the southern islands than in the northern islands. Stressed-coral cover, observed during towed-diver benthic surveys, was higher in the southern islands than in the northern islands, especially in 2007. Bleaching, siltation, and typhoons may have affected coral health, particularly around Rota, where some of the lowest coral cover values archipelago-wide were detected in the 3 MARAMP survey years.

Overall mean prevalence of coral bleaching and disease, based on REA benthic surveys conducted in 2007, was highest around the southern islands, a pattern exemplified by the presence of hot spots at Guam. Because elevated water temperatures and anthropogenic disturbances have been identified as environmental drivers of disease, the populated, southern

islands may have a greater risk of coral bleaching and marine disease outbreaks than do the mostly uninhabited northern islands. Also, a large percentage of disease cases seen in the Mariana Archipelago disproportionately affected important coral reef building taxa, including hard corals in the families Poritidae, Acroporidae, and Faviidae as well as calcium-carbonate-producing crustose coralline red algae. Another factor influencing the condition of coral reef ecosystems in the Mariana Archipelago was the fluctuating populations of the corallivorous COTS, which were observed in some areas at densities high enough to suggest that an outbreak was occurring.

Total mean fish biomass, based on REA surveys for fishes from all species and size classes, was lower at the populated, southern islands than at the northern islands, with overall means for the two island groups at 3.63 kg 100 m^{-2} versus 12.00 kg 100 m^{-2}. This difference was the result of lower fish abundances coupled with smaller average fish sizes at the southern islands compared to the northern islands. Fish species richness followed a similar pattern. MARAMP data are in agreement with other studies that suggest lower fish biomass and sizes are likely to occur in association with higher densities of human populations and greater resource use. In addition, the overall abundance of marine debris as observed in towed-diver surveys was greater around the southern islands than around the northern islands, with the greatest mean numbers of sightings of derelict fishing gear and other man-made objects, such as anchors, ground tackle, mooring blocks, and metal scrap, found at Guam and Tinian.

As indicated above, many of the anthropogenic activities and associated effects to the coral reef ecosystems in the Mariana Archipelago are concentrated around the populated, southern islands. Conversely, the 9 northern islands are sparsely inhabited with total fluctuating populations of 0–100 persons on Agrihan, Pagan, Alamagan, and Anatahan since WWII. With relatively low levels of anthropogenic disturbance, other than feral animals, introduced species, and some resource overuse at the northern islands, natural events, such as storms, thermal stress, and volcanic eruptions, are among the main environmental factors that affect the coral reef ecosystems there.

Geologically, all the northern islands are active or dormant stratovolcanoes, formed along the tectonically active part of the Mariana Arc. Many of these islands have erupted on several occasions within recorded history. Except for Pagan and Agrihan, which have land areas of 48 and 44 km^2, the northern islands are the smallest in the Mariana Archipelago, with land areas of 2–34 km^2. These islands are characterized by moderate to steep slopes (means of ~ 20°–25° on the seafloor) and covered with layers of hardened lava, cinder, or ash. Oceanographically, climatologies show that the northern islands exhibit cooler SSTs, are less windy, have weaker surface currents, and are more productive compared to the southern islands, regardless of season. Episodic volcanic eruptions, ash discharge, and landslides can effectively modify the quality and chemistry of the surrounding coastal waters on a temporal basis.

The notion that potential habitat size, in concert with disturbance frequency (primarily volcanic activity) is a likely predictor of taxonomic richness is exemplified in results from REA benthic surveys conducted at Farallon de Pajaros, which has a land area of 2 km^2 and had frequent volcanic activity during the 19th century and recurrent eruptions in the 1940s to 1960s. Farallon de Pajaros harbored the lowest total and overall mean richness of corals and macroalgae recorded at an island in the Mariana Archipelago, with overall mean numbers of genera per site of 7.6 for corals and 6 for macroalgae across the 3 MARAMP survey years. Comparatively, Pagan, which has the largest land area among the northern islands, harbored the greatest coral and algal diversity observed in the northern islands over the 3 survey years, with 32 total coral genera and 40 total macroalgal genera enumerated. Despite these general patterns, however, some taxa, including the hard coral genera *Merulina* and *Euphyllia* and the red algae *Cheilosporum* and *Dasya*, were found at 2–4 northern islands but rare or absent in the southern islands, suggesting that the northern islands offer biological and environmental conditions favorable for the proliferation of selected coral and algal taxa. Similarly, the northern islands also harbored the largest populations of giant clams of the genus *Tridacna*.

Macroalgal cover from REA and towed-diver surveys followed the same north–south pattern as algal richness, with values lower at the volcanic, northern islands than at the southern islands. In contrast, the opposite pattern was observed for estimates of live coral cover from REA and towed-diver benthic surveys conducted in 2007, except for at Farallon de Pajaros and Pagan. Excluding these two islands, coral cover was moderately high at the northern islands, with overall sample means from REA benthic surveys ranging from 15.4% at Guguan to 34.1% at Maug. Selected habitats at Maug, such as the eastern flank of the caldera, harbored exceptionally high cover (~ 70%) aggregations of the hard coral *Porites rus* (Fig. 3.11a). It appeared that Farallon de Pajaros, where overall mean coral cover was 3.6% from REA surveys, was geologically too unstable to promote the development of substantial coral communities and reef buildups. Alternatively, the low coral cover observed at Pagan, with an overall sample mean of 10.6%, may not have been caused by geological and volcanic activity but rather may have resulted from COTS outbreak conditions observed around much of Pagan in 2005 and 2007

Figure 3.11a. Towering *Porites rus* formations on the eastern side of Maug's caldera. *NOAA photo by Bernardo Vargas-Ángel*
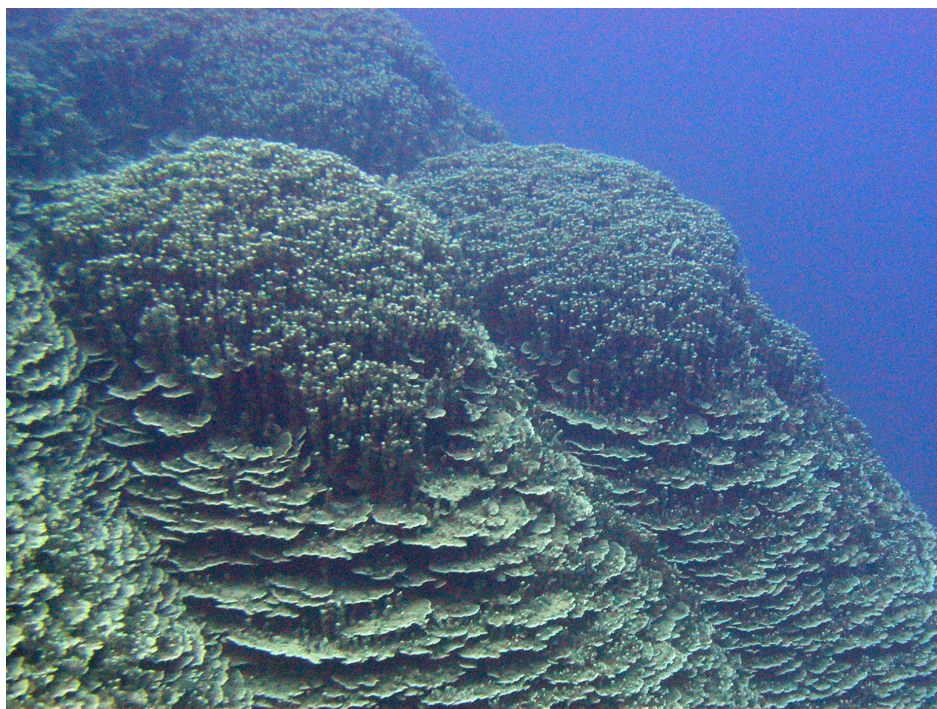
Compared to observations at the southern islands, coral bleaching and coral and coralline-algal diseases occurred at lower levels or were absent in the northern islands of the Mariana Archipelago, based on estimates of prevalence or densities from REA benthic surveys conducted during MARAMP 2007. The presence and distribution of coral and coralline-algal disease corroborates the potential linkage with higher water temperatures and the presence of humans, since only 26% and 13% of disease cases, respectively, were documented at the largely uninhabited, northern islands.

Mean total fish biomass from REA surveys was more than 3 times greater in the northern islands than in the southern islands of the Mariana Archipelago, a result of greater fish abundance and average sizes. A similar pattern of species richness emerged: the northern islands exhibited higher average richness, with a range of 30.6–43.6 species 100 m^{-2} excluding Anatahan, than did the southern islands, with a range of 20.2–30.0 species 100 m^{-2}. Biomass of herbivorous fishes, including surgeonfishes (Acanthuridae) and parrotfishes (Scaridae), was twice as high at the northern islands than at the southern islands. Piscivores, including jacks (Carangidae) and sharks (Carcharhinidae and Ginglymostomatidae), accounted for 34% of the total fish biomass in the northern islands, and mean biomass of piscivores was more than 13 times greater in the northern islands than in the southern islands. Data from towed-diver fish surveys in forereef habitats show similar broad patterns in shark abundance; the number of sharks encountered per unit area surveyed in the northern islands was 174.5 individuals km^{-2}—nearly 10 times the abundance recorded in the southern islands.

Lastly, a general pattern of decreasing conditions from the northern islands to the southern islands was observed in the Archipelagic Coral Reef Condition Index, Archipelagic Benthic Condition Index, and Archipelagic Fish Condition Index, the composite metrics of biological variables derived to describe the relative status of coral reefs throughout the Mariana Archipelago. The geographic regions of the southern islands of Guam, Rota, Tinian, Aguijan, and Saipan, for the most part, had low or declining ranks in the overall Archipelagic Coral Reef Condition Index, compared to the conditions observed and ranked for other regions in this archipelago. The main exception was the east region of Saipan, where marine protected areas have been established. Maug, Farallon de Pajaros, Alamagan, and Asuncion had the highest ranks in the Archipelagic Coral Reef Condition Index, attributable to high coral cover, low stressed-coral cover, and high large-fish density and biomass. Three of these islands, Maug, Farallon de Pajaros, and Asuncion, are the northernmost islands of the Mariana Archipelago and are part of the Marianas Trench Marine National Monument.

Errata

Erratum 1—Correction in Chapter 3: "Archipelagic Comparisons," Section 3.1: "Geopolitical Context," P. 1, Table 3.1a:

The brown tree snake symbol was changed from black to grey in the "Animal Threats" column of the rows for Saipan, Tinian, and Rota. A legend for the new grey symbol was added, stating "Brown tree snake sighted but not established." A personal communications was added to the citations in the table caption, "M Onni, CNMI Division of Fish and Wildlife, pers. comm."

Although sightings of the brown tree snake (*Boiga irregularis*) have been reported for Saipan, Tinian, and Rota (Marianas Avifauna Conservation Working Group 2008), efforts by the Brown Tree Snake Program of the Commonwealth of the Northern Mariana Islands (CNMI) Division of Fish and Wildlife (DFW) to keep populations from becoming established outside of Guam have been effective, as the last live snake captured and dead snake found in the CNMI were recorded on Saipan in 2000 and on Rota in 2009, respectively (M Onni, CNMI DFW, pers. comm.)

Erratum 2—Correction in Chapter 4: "Guam & Adjacent Reefs," Section 4.1.4: "Economy," P. 7, lines 1 and 2:

This sentence was redacted: "Two fishing methods have been banned: (1) use of scuba and artificial light for spearfishing and (2) use of monofilament gill nets."

These two fishing methods have not been banned in Guam.

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